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ARCTIC AND SUBARCTIC ATMOSPHERES, 0 TO 90 KM.(U)

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Arctic and Subarctic Atmospheres, 0 to 90 km

ALLEN E. COLE
ARTHUR J. KANTOR

11 February 1977

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METEOROLOGY DIVISION   PROJECT 8624
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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

John Howard

Chief Scientist

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Sets of mean monthly reference atmospheres that describe seasonal changes in the vertical distributions of temperature, density, and pressure at altitudes up to 90 km are presented for latitudes 60°N and 75°N. Also provided are specialized atmospheric models that reflect longitudinal differences in the vertical structure of temperature and density at these latitudes. Estimates of the seasonal, day-to-day, diurnal, and spatial variations are given with special emphasis placed on density.

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Arctic and Subarctic Atmospheres 0 to 90 km

1. INTRODUCTION

Sets of monthly reference atmospheres that show the seasonal changes in the vertical distributions of temperature, pressure, and density for altitudes up to 90 km are presented for latitudes 60°N and 75°N. Models for various longitudes depict the longitudinal variations of these parameters during the winter at these latitudes. Estimates of the magnitude of the diurnal, day-to-day, and spatial variability of temperature and density are included.

These arctic and subarctic atmospheres are part of a more comprehensive effort sponsored by the U.S. Committee on Extension to the Standard Atmosphere (COESA) to develop sets of monthly reference atmospheres from the surface to 90 km at 15° intervals of latitude between the equator and the North Pole. They are intended to replace the U.S. Standard Atmosphere Supplements, 1966, which were prepared by the COESA Working Group more than ten years ago. Monthly models for low latitudes and midlatitudes have already been completed.[1,2]

There has been a substantial increase in the number of meteorological rocket observations taken on a routine basis in arctic and subarctic regions since preparation of the U.S. Standard Atmosphere Supplements, 1966. Sufficient data are now

(Received for publication 11 February 1977)

1. Cole, A. E., and Kantor, A. J. (1975) Tropical Atmospheres, 0 to 90 km, AFCRL-TR-75-0527.
2. Kantor, A. J., and Cole, A. E. (1976) Monthly Midlatitude Atmospheres, Surface to 90 km, AFGL-TR-76-0140.

available from observations taken at locations near latitudes 60° and 75°N for a relatively detailed analysis of the seasonal, day-to-day, latitudinal, and longitudinal (140°W to 10°W) variations of the thermodynamic properties of the atmosphere for altitudes up to at least 50 km. A much smaller number of measurements from grenade, pressure gauge, and falling sphere experiments are available for altitudes between 50 and 90 km. Due to the sparsity of data above 50 km, the periodic and day-to-day variations that are given for these altitudes are more speculative than those provided for altitudes below 50 km.

For the purposes of this report, both meteorological rocket network (MRN) and experimental rocket data were combined with radiosonde observations to produce temperature, pressure, and density models from the surface to 90 km. Because the three sets of data are for different periods of record and were obtained with different types of sensors, some subjective judgment was exercised to obtain smooth temperature-height profiles in areas where data sets overlapped.

2. BASIC ASSUMPTIONS AND FORMULAS

The monthly atmospheres are defined by temperature-altitude profiles in which vertical gradients of temperature are linear with respect to geopotential altitude. It is assumed that the air is dry, is in hydrostatic equilibrium, and behaves as a perfect gas. The molecular weight of air at sea level, 28.9644 $kg(k\text{-}mol)^{-1}$, is assumed to be constant to 90 km. Actually, dissociation of molecular oxygen begins to take place near 80 km and molecular weight starts decreasing slowly with height. Consequently, the molecular-scale temperatures (T_M) given in Appendix A for altitudes above 80 km are slightly, but not significantly, larger than the ambient kinetic temperature (T), as $T_M = (Mo/M)T$, where Mo is sea-level molecular weight and M is the molecular weight of air at a specific altitude. Molecular weight is constant below 80 km; therefore, molecular-scale and ambient temperatures are identical at these altitudes.

Numerical values for the various thermodynamic and physical constants used in computing the tables of atmospheric properties (Appendix A) for the mean monthly arctic and subarctic atmospheres are identical to those used in the preparation of the U.S. Standard Atmosphere, 1976, with two exceptions. Surface conditions for the 60°N and 75°N atmospheres are based on mean monthly sea-level values of pressure and temperature for the appropriate latitude rather than on standard conditions. The acceleration due to gravity at sea level for latitudes 60° and 75°N were obtained from the following expression by Lambert[3] in which gravity, g, varies with latitude ϕ:

3. List, R.J. (ed) (1968) Smithsonian Meteorological Tables, Smithsonian Inst. Press, Washington, D.C.

$$g_\phi = 9.780356\,(1 + 0.0052885 \sin^2 \phi - 0.0000059 \sin^2 2\phi)\ . \qquad (1)$$

The values for sea-level gravity from Lambert's formula for latitudes 60° and 75°N are 9.81911 and 9.82860 m sec^{-2}, respectively.

2.1 The Static Atmosphere and Perfect Gas Law

The air is assumed to be in hydrostatic equilibrium and to satisfy the differential equation

$$dP = -\rho\, g\, dZ \qquad (2)$$

which relates air pressure (P) to density (ρ), acceleration of free fall (g), and height (Z). The perfect gas law relates air pressure to density and temperature as follows:

$$P = \frac{\rho R^* T_M}{M_o} \qquad (3)$$

where R^* is the universal gas constant, 8.31432×10^3 joules K^{-1} (k-mol)$^{-1}$.

2.2 Geopotential

The relationship between geopotential altitude and geometric altitude is the same as that used for the U.S. Standard Atmosphere Supplements, 1966:

$$H = \left(\frac{r_\phi Z}{r_\phi + Z}\right)\left(\frac{g_\phi}{g_o}\right) \qquad (4)$$

where H is the geopotential altitude, Z the geometric altitude, r_ϕ the effective earth radius, g_ϕ the sea-level value for acceleration of gravity at a specific latitude ϕ, as given by Lambert's equation,[3] and g_o (9.80665) the sea-level value of the acceleration of gravity adopted for the U.S. Standard Atmosphere.

2.3 Pressure

Vertical distributions of pressure were computed from appropriate temperature-height profiles and associated mean monthly surface pressures, according to the following barometric equations:

$$\frac{P}{P_b} = \left(\frac{T_{Mb}}{T_{Mb + Lh}}\right)^{\frac{g_o M_o}{R^* L}} \quad (L \neq 0) \qquad (5)$$

$$\frac{P}{P_b} = \exp\left(\frac{-g_o M_o h}{R^* T_{Mb}}\right) \quad (L = 0) \tag{6}$$

where $h = H - H_b$; H_b is the geopotential altitude at the base of a particular layer characterized by a specific value of L, which is the vertical gradient of molecular-scale temperature with geopotential height; and T_{Mb} and P_b are the respective values of temperature and pressure at altitude H_b.

3. DATA

Initial sea-level pressures for each atmosphere were taken from mean monthly sea-level charts for the Northern Hemisphere.[4,5] Mean monthly temperature-height profiles for altitudes up to 30 km were obtained for latitudes 60° and 75°N by giving equal weight to radiosonde temperatures[6-9] interpolated for each 10 degrees of longitude.

Temperature and density distributions between 30 and 55 km are based on MRN observations[10] taken at the locations given in Table 1 and the sets of 5-, 2-, and 0.4-mb constant-pressure maps prepared on a weekly basis for the years 1964 through 1968 and from January 1972 through June 1973.[11-16] The MRN data were corrected as suggested by Krumins and Lyons[17] for altitudes between 30 and 50 km. Since thermistor measurements are subject to large corrections above 50 km, they were not used for altitudes above 50 km. The temperature distributions between 50 and 90 km are based on values derived from grenade, falling sphere, and pressure gauge experiments conducted at locations indicated in Table 1.[18-32]

Temperature-height data were also taken from mean monthly pressure-height maps for 5-, 2-, and 0.4-mb levels. These maps were developed from grid-point data taken from a series of weekly pressure-height maps prepared by the National Meteorological Center.[11-16] Mean January and July pressure-height and temperature maps for the 0.4-mb level are shown in Figures 1 and 2. During the winter months there is considerable longitudinal asymmetry in the mean monthly temperature and pressure patterns north of 45° latitude. In summer the circulation patterns are nearly symmetrical about the pole, and the mean monthly isotherms and pressure-height contours at these altitudes parallel the latitude circles.

(Because of the large number of references cited above, they will not be listed here. See References on page 41 for References 4 through 32.)

Table 1. Observational Sites

Stations	Latitude	Longitude	Period of Record
Meteorological Rockets			
White Sands	32°N	106°W	Jan 1965 – Dec 1975
Point Mugu	34°N	119°W	Jan 1965 – Dec 1975
Wallops Island	38°N	75°W	Jan 1965 – Dec 1975
Volgograd	49°N	44°E	Jan 1968 – Dec 1974
Shemya	53°N	174°E	Jan 1975 – Mar 1976
Primrose Lake	55°N	110°W	Apr 1967 – Dec 1975
West Geirinish	57°N	7°W	Jan 1965 – Jan 1972
Churchill	59°N	94°W	Jan 1965 – Dec 1975
Ft. Greely	64°N	146°W	Jan 1965 – Dec 1975
Thule	77°N	69°W	Jan 1965 – Dec 1975
Heiss Island	81°N	58°E	Jan 1968 – Dec 1974
Experimental Rockets			
Woomera	31°S	137°E	1957 – 1973
Ascension Island	8°S	14°W	1964 – 1965
Natal	6°S	35°W	1966 – 1968
Kourou	5°N	52°W	1971
White Sands	32°N	106°W	1965 – 1971
Wallops Island	38°N	75°W	1961 – 1971
Churchill	59°N	94°W	1957 – 1971
Barrow	71°N	157°W	1965 – 1972

4. ANALYSIS

Medians of monthly temperatures and densities were derived at 5-km intervals of altitude between 30 and 90 km from meteorological and experimental rocket observations taken at the locations given in Table 1. Bimonthly running medians were obtained for altitudes and locations where data for one or more months were missing.

The median monthly temperatures and densities for each location and level were subjected to harmonic analysis for annual and semiannual cycles. The analyses smoothed the data and gave regression equations of the form

$$Y = \overline{Y} + A_1 \sin(x+\phi_1) + A_2 (\sin 2x+\phi_2) \quad (7)$$

where A is amplitude, Y is either density or temperature, $\overline{Y}$ is the mean annual value, $x = iz$, $z = 360°/\text{period}$, $i = o, 1, 2 \text{ --- } 11$, where o represents 15 January, 1 represents 15 February, etc.

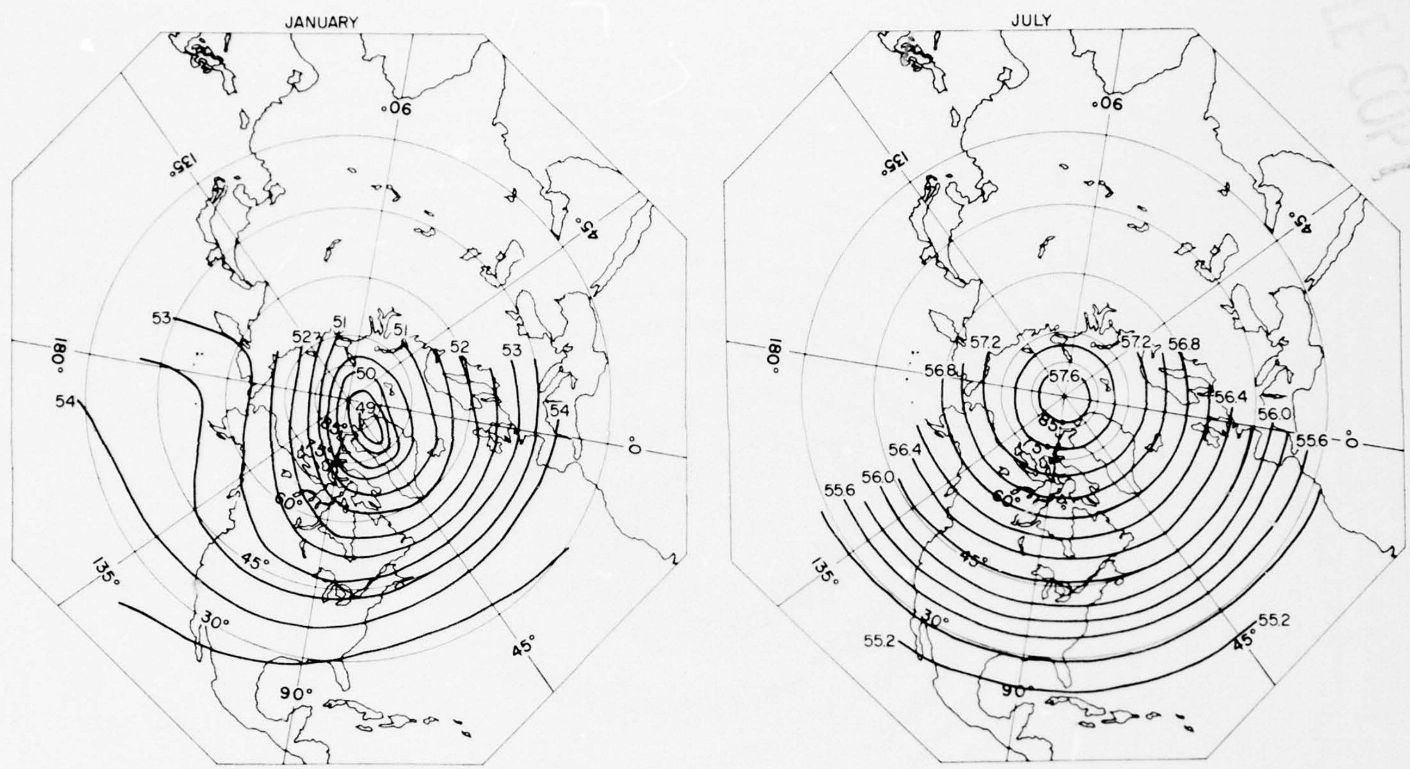

Figure 1. Mean January and July Pressure-Height Maps (km) for 0.4 mb

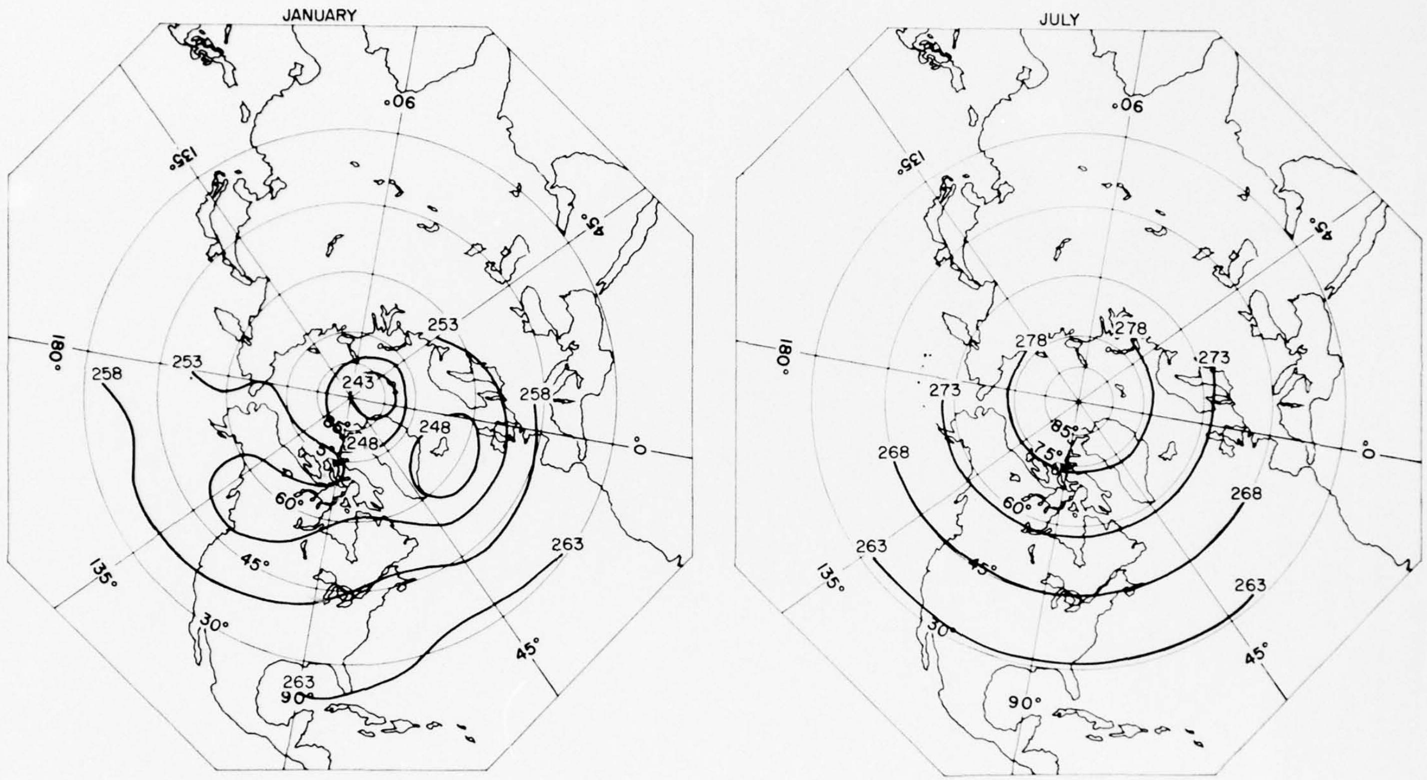

Figure 2. Mean January and July Temperature Maps (°K) for 0.4 mb

Curves representing the sum of the annual and semiannual cycles of temperature for altitudes between 25 and 80 km are shown in Figure 3 for Churchill, Fort Greely, Thule, and Point Barrow. Curves for altitudes between 30 and 50 km are based on MRN observations; those for altitudes above 50 km are based on experimental observations.

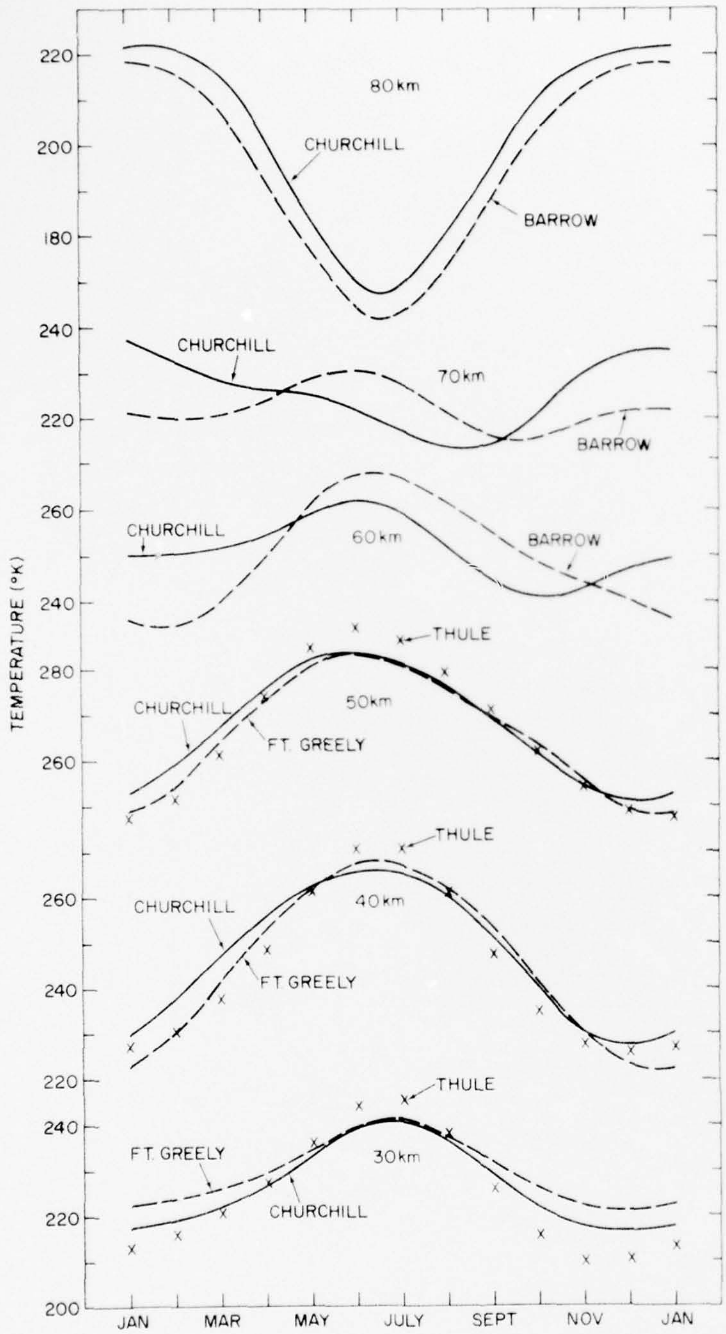

Figure 3. Sum of the Annual and Semi-annual Temperature Cycles Observed at Churchill, Fort Greely, Barrow, and Thule

Monthly temperatures from the individual harmonic curves and from the mean monthly maps for 5, 2, and 0.4 mb were plotted vs latitude for 5-km height increments between 30 and 80 km. Estimates of the temperatures at 60° and 75°N were then obtained by fitting latitudinal temperature curves to these data. Third degree polynomial curves appeared to provide reasonable estimates of the temperatures at 15° intervals of latitude from the North Pole to the Equator at altitudes below 55 km where data are relatively plentiful as well as at altitudes above 55 km during the summer months when longitudinal and latitudinal temperature variations are relatively small. However, during the Northern Hemisphere winter when longitudinal and latitudinal temperature variations are large, especially above 50 km, the polynomials do not provide realistic estimates of the latitudinal temperature gradients for altitudes between 50 and 90 km. Fourth and fifth degree polynomial fits provided even poorer estimates. Third degree polynomial curves for January and July at 30 and 75 km are shown in Figures 4 and 5, and examples of the subjective curves used for the 60-, 70-, and 80-km levels in January are shown in Figure 6.

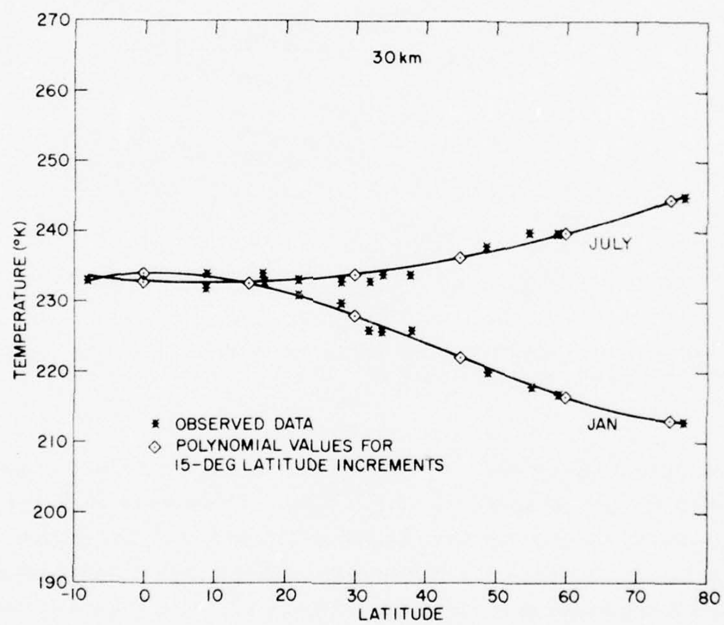

Figure 4. Latitudinal Distribution of Mean Monthly 30-km Temperatures for January and July

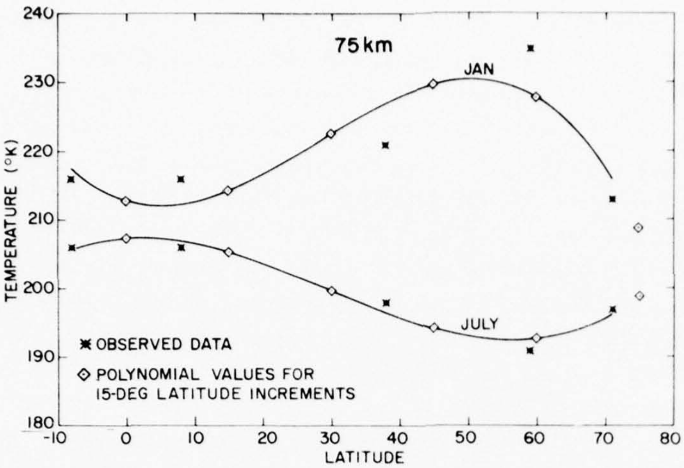

Figure 5. Latitudinal Distribution of Mean Monthly 75-km Temperatures for January and July

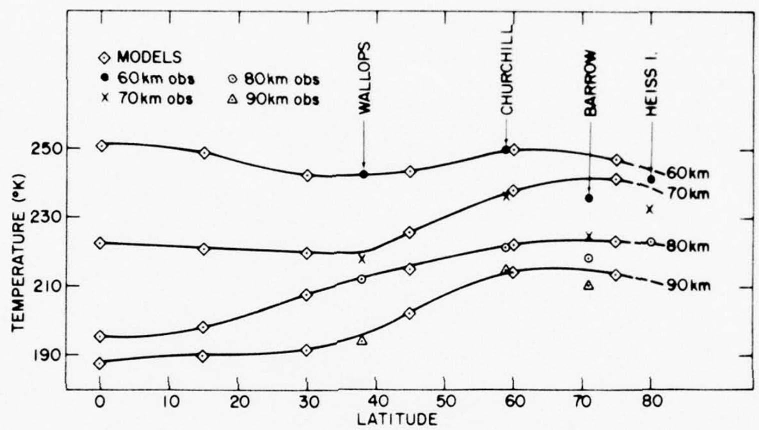

Figure 6. Subjective Curves for Mean Monthly 60-, 70-, and 80-km Temperatures in January

Median monthly temperatures were obtained from available soundings for 1-km intervals of altitude from 45 to 55 and 75 to 85 km. These were analyzed to obtain realistic estimates of the variations in height and thickness of the isothermal layers associated with the stratopause and mesopause. Time cross-sections of the adopted monthly temperatures for 60° and 75°N are shown in Figures 7 and 8 for altitudes between 10 and 90 km.

The temperature-height profiles adopted for each of the monthly atmospheres at 60° and 75°N are defined in Table 2. The vertical temperature gradients between breakpoints are linear with geopotential altitude.

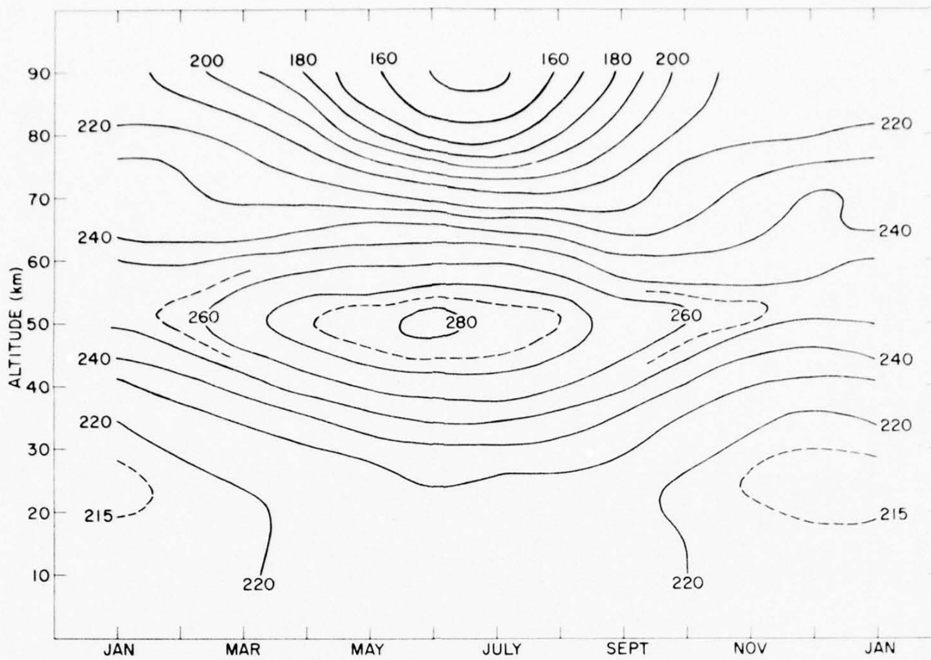

Figure 7. Mean Monthly Temperature-Height Cross-Section for 60°N

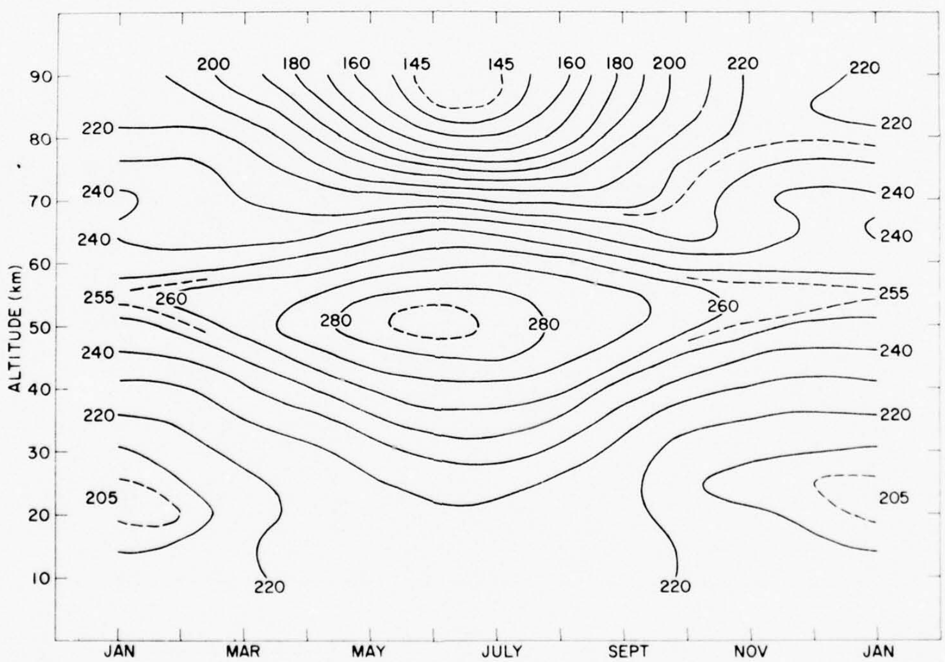

Figure 8. Mean Monthly Temperature-Height Cross-Section for 75°N

Table 2a. 60°N Temperature-Height Profiles to 90 km

MONTH	SURFACE PRESSURE	BREAK POINTS IN KILOMETERS (GEOPOTENTIAL) AND TEMPERATURE (°K)											
	(mb)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)
JAN	1014.4	(0) (35.0) (64.5)	257.15 221.15 238.65	(1.0) (40.0) (71.0)	259.15 226.65 238.65	(3.5) (45.0) (83.0)	251.15 244.15 214.65	(8.5) (50.0) (89.0)	217.15 251.15 214.65	(15.0) (54.5)	217.15 251.15	(25.0) (59.5)	212.15 250.15
FEB	1014.6	(0) (32.0) (64.5)	256.65 223.15 234.15	(1.0) (37.0) (74.5)	258.15 228.15 230.15	(3.5) (44.5) (87.0)	256.15 249.15 205.15	(8.5) (49.5) (89.0)	218.65 255.65 205.15	(15.0) (53.0)	218.65 255.65	(22.0) (59.5)	215.15 249.15
MAR	1014.3	(0) (35.0) (75.5)	261.65 231.15 226.15	(3.0) (45.0) (88.5)	258.65 257.15 193.65	(9.0) (49.0) (89.0)	219.65 265.15 193.65	(15.0) (52.5)	219.65 265.15	(20.0) (59.5)	218.65 251.15	(30.0) (65.5)	222.65 230.15
APR	1013.4	(0) (45.0)	269.15 268.15	(4.0) (49.0)	257.15 274.15	(9.0) (52.5)	222.15 274.15	(25.0) (64.5)	222.15 238.15	(30.0) (74.5)	227.65 217.15	(35.0) (89.5)	239.15 178.15
MAY	1013.3	(0) (48.0)	276.65 279.15	(4.0) (50.5)	260.65 279.15	(9.0) (63.0)	223.65 249.15	(25.0) (83.0)	223.65 169.15	(32.5) (88.0)	240.15 163.15	(42.5) (89.0)	268.15 163.15
JUNE	1011.0	(0) (47.0)	282.65 280.65	(4.0) (52.0)	266.65 280.65	(10.0) (64.0)	224.65 244.65	(21.0) (81.5)	224.65 157.15	(31.0) (88.5)	240.65 150.15	(41.0) (89.0)	268.65 150.15
JULY	1009.9	(0) (47.0)	287.15 279.15	(5.0) (51.0)	260.15 279.15	(10.0) (61.0)	225.15 255.15	(23.0) (81.0)	225.15 157.15	(29.5) (89.0)	238.15 149.15	(44.5)	227.15
AUG	1010.7	(0) (47.5)	284.15 275.15	(5.0) (51.5)	262.15 275.15	(10.0) (61.5)	224.15 247.15	(21.5) (69.0)	224.15 214.15	(31.5) (79.0)	239.15 180.15	(43.5) (89.0)	269.15 160.15
SEPT	1011.3	(0) (48.0)	281.15 267.15	(4.0) (50.5)	263.15 267.15	(10.0) (68.0)	221.15 218.15	(24.0) (88.0)	221.15 182.15	(34.0) (89.0)	237.15 182.15	(44.0)	261.15
OCT	1010.6	(0) (40.0) (89.0)	275.15 240.15 204.15	(4.0) (48.0)	259.15 260.15	(10.0) (52.5)	220.15 260.15	(17.5) (62.5)	220.15 233.15	(22.5) (73.5)	217.15 222.15	(32.5) (82.5)	225.15 204.15
NOV	1012.5	(0) (40.0) (79.0)	266.15 230.65 216.65	(4.0) (45.0) (89.0)	256.15 242.15 216.65	(9.0) (49.5)	218.65 255.65	(15.0) (52.5)	218.65 255.65	(25.0) (62.5)	214.65 237.65	(35.0) (69.0)	222.65 237.65
DEC	1012.6	(0) (35.0) (82.0)	259.15 219.65 211.65	(1.0) (40.0) (89.5)	259.65 227.15 222.15	(3.5) (50.0)	255.15 250.15	(8.5) (56.0)	217.65 250.15	(15.0) (64.5)	217.65 241.65	(25.0) (69.5)	210.65 241.65

Table 2b. 75°N Temperature-Height Profiles to 90 km

MONTH	SURFACE PRESSURE	BREAK POINTS IN KILOMETERS (GEOPOTENTIAL) AND TEMPERATURE (°K)											
	(mb)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)	(Alt)	(°K)
JAN	1014.7	(0) (55.0)	248.15 255.15	(1.5) (65.0)	254.15 238.15	(8.5) (70.0)	215.65 242.15	(21.5) (84.0)	202.65 214.15	(29.0) (89.0)	207.15 214.15	(53.0)	255.15
FEB	1015.9	(0) (40.5)	247.65 230.15	(1.5) (52.5)	253.65 260.15	(3.0) (55.0)	247.65 260.15	(8.0) (64.0)	216.15 233.15	(15.5) (71.5)	211.65 236.15	(20.5) (89.0)	204.15 208.15
MAR	1017.5	(0) (27.5) (88.5)	248.65 219.15 193.15	(1.5) (39.5)	253.15 237.15	(2.5) (51.5)	250.15 267.15	(8.5) (54.5)	217.15 267.15	(14.5) (64.5)	220.15 232.15	(20.0) (74.5)	214.65 228.15
APR	1016.9	(0) (38.0)	255.15 242.15	(1.5) (48.0)	256.65 274.15	(2.5) (53.0)	253.15 274.15	(8.5) (65.5)	220.15 234.15	(11.0) (75.5)	224.15 215.15	(28.0) (88.5)	224.15 176.15
MAY	1017.0	(0) (48.0)	264.15 283.15	(2.0) (53.0)	263.15 283.15	(8.5) (68.0)	224.15 232.15	(12.5) (80.5)	228.15 172.15	(25.5) (89.0)	228.15 155.15	(30.5)	234.15
JUNE	1013.1	(0) (47.5)	272.65 285.65	(2.5) (53.0)	268.15 285.65	(8.5) (64.5)	226.15 251.15	(12.0) (82.0)	229.65 146.15	(21.0) (89.0)	229.65 142.65	(25.0)	231.65
JULY	1011.1	(0) (46.0)	275.65 283.65	(2.0) (53.5)	273.65 283.65	(9.0) (61.5)	228.15 263.65	(14.0) (81.5)	230.15 147.65	(25.0) (89.0)	230.15 144.65	(35.0)	256.15
AUG	1011.5	(0) (53.0)	274.65 278.15	(2.5) (59.0)	270.65 266.15	(9.0) (79.0)	225.15 172.15	(15.0) (89.0)	228.15 156.15	(26.5)	228.15	(46.5)	278.15
SEPT	1011.6	(0) (28.0) (89.0)	270.15 222.65 180.65	(1.5) (40.0)	267.15 246.65	(9.0) (47.5)	222.15 270.65	(11.5) (55.0)	224.65 270.65	(16.5) (67.0)	224.65 222.65	(20.5) (88.0)	222.65 180.65
OCT	1009.2	(0) (50.0)	262.65 263.15	(2.5) (54.5)	258.65 263.15	(8.5) (64.5)	219.65 227.15	(16.0) (72.5)	219.65 227.15	(25.0) (83.5)	210.65 205.15	(35.0) (89.0)	222.65 205.15
NOV	1013.4	(0) (46.0) (89.0)	253.15 242.15 221.15	(1.5) (51.0)	256.15 258.15	(8.5) (54.5)	217.65 258.15	(13.5) (62.0)	217.65 234.15	(23.5) (70.0)	207.65 238.15	(30.5) (78.5)	211.15 221.15
DEC	1012.8	(0) (54.5)	251.15 256.65	(2.0) (62.0)	254.15 240.15	(8.5) (70.0)	215.15 244.15	(26.0) (82.5)	204.65 216.65	(42.0) (89.5)	228.65 227.15	(52.0)	256.65

5. DENSITY

Densities computed from the temperature-height profiles that were adopted for the monthly atmospheres for 60° and 75°N are compared to observed values at Churchill, Fort Greely, and Primrose Lake in Figure 9, and to those at Barrow and Thule in Figure 10. Densities are given as percent departures from 1976 standard densities. The observed densities, which are based on MRN measurements for altitude between 30 and 50 km, are in good agreement with the models. However, model densities for the summer months at altitudes above 50 km are higher than the observed values derived from grenade, pressure gauge, and falling sphere experiments at Churchill and Barrow. Much of these summer differences may be due to variations in observation times. Model temperatures for altitudes between 25 and 55 km are based on MRN measurements normally taken close to local noon, whereas the experimental temperature observations, on which the densities at altitudes from 55 to 90 km are based, are usually taken during twilight hours when temperatures between 20 and 55 km are normally lower.

Due to warmer daytime temperature at altitudes from 25 to 50 km, the MRN densities, which are essentially the same as the model densities at 50- and 55-km altitudes, are higher than densities derived from grenade and pressure-gauge experiments for 55 km. This bias between the model and experimentally observed densities appears at all altitudes between 55 and 90 km. The differences between the model densities and observed values at specific locations during the winter and transitional months is partially due to longitudinal variations in the mean monthly density structure at these latitudes as well as to latitudinal differences in that Barrow is at 71°N and Churchill is at 59°N. The observed phases and amplitudes of the annual and semiannual oscillations of density above 50 km, however, are in good agreement with the models.

6. LONGITUDINAL VARIATIONS

In order to illustrate the magnitude of the longitudinal variations in arctic and subarctic regions during winter, atmospheric models depicting mean January conditions between the surface and 55 km were developed at 10°, 100°, and 140°W for 60°N and at 10° and 140°W for 75°N. The models are based on radiosonde observations, constant-pressure maps at 5, 2, and 0.4 mb, rocketsonde observations, hydrostatic build-up techniques from the 5- and 10-mb levels, and the thermal wind equation. Tables of the atmospheric properties for these January models at 60° and 75°N are given in Appendix A; temperature-height profiles are shown in Figures 11 and 12, respectively, and are defined in Table 3.

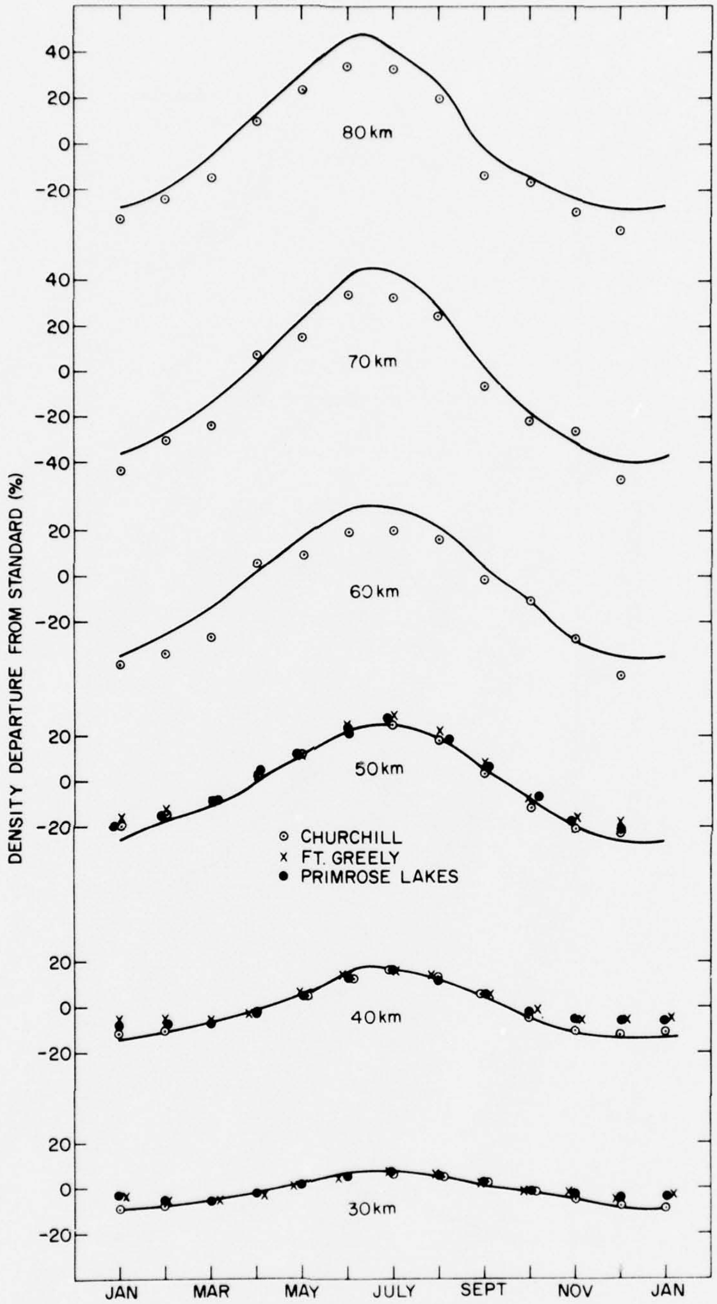

Figure 9. Comparison of Observed Densities at Churchill, Ft. Greely, and Primrose Lake With Model Densities for 60°N

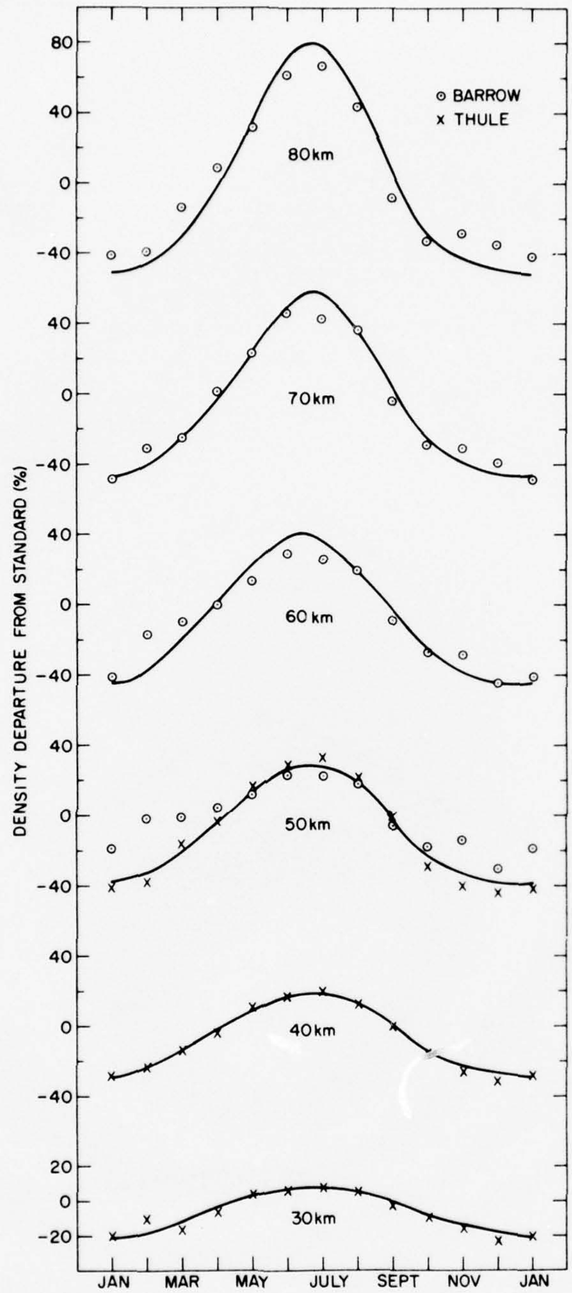

Figure 10. Comparison of Observed Mean Monthly Densities at Barrow and Thule With Model Densities for 75°N

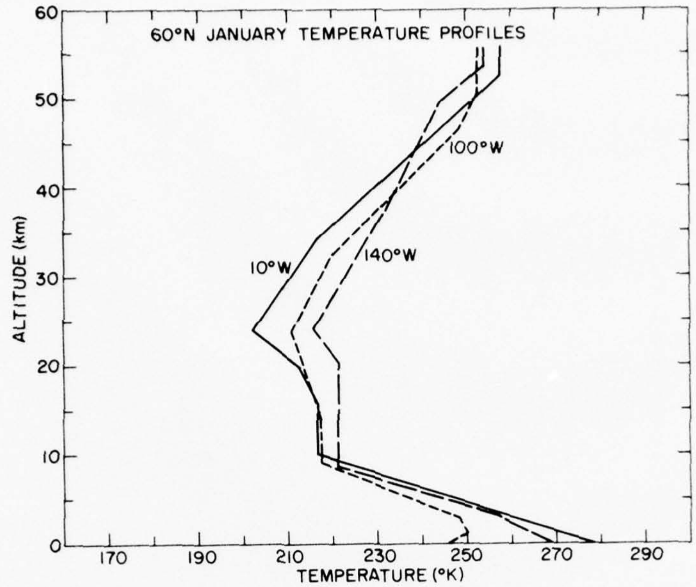

Figure 11. Temperature-Height Profiles for the 60°N Models at 10°, 100°, and 140°W

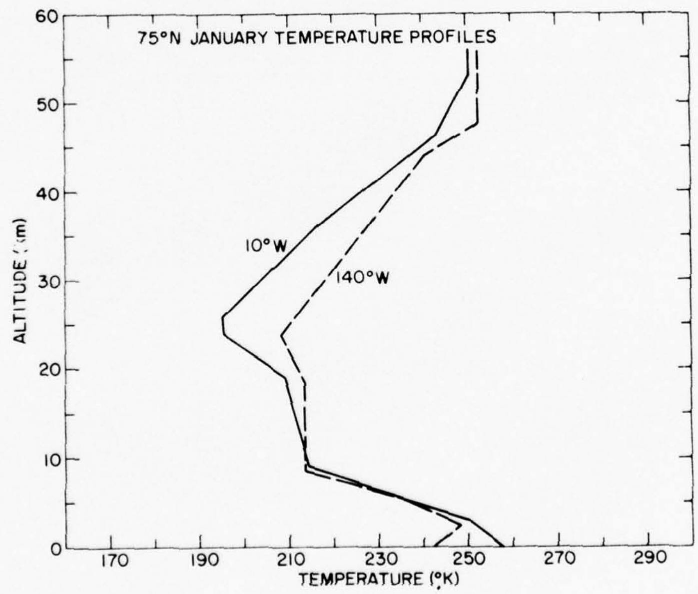

Figure 12. Temperature-Height Profiles for the 75°N Models at 10° and 140°W

Table 3. January Temperature-Height Profiles to 55 km for Specified Longitudes at 60° N and 75° N

LAT. / LONG.	SURFACE PRESSURE	BREAK POINTS IN KILOMETERS (GEOPOTENTIAL) AND TEMPERATURE (°K)					
	(mb)	(Alt) (°K)	(Alt) (°K)	(Alt) (°K)	(Alt) (°K)	(Alt) (°K)	(Alt) (°K)
60° N, 10° W	1002.5	(0) 278.15	(10.0) 216.15	(16.0) 216.15	(20.0) 212.15	(24.0) 202.15	(34.0) 216.15
		(52.0) 257.55	(55.0) 257.55				
60° N, 100° W	1017.5	(0) 246.15	(1.0) 250.15	(3.0) 247.15	(9.0) 217.15	(14.0) 217.15	(24.0) 211.15
		(32.0) 219.15	(38.0) 228.15	(46.0) 248.15	(50.0) 252.15	(55.0) 252.15	
60° N, 140° W	1010.25	(0) 269.15	(3.5) 255.15	(8.5) 221.15	(20.0) 221.15	(24.0) 215.15	(39.0) 233.15
		(49.0) 244.15	(53.0) 254.15	(55.0) 254.15			
75° N, 10° W	1006.5	(0) 257.65	(3.0) 250.15	(9.0) 214.15	(19.0) 209.15	(24.0) 195.15	(26.0) 195.15
		(36.0) 216.15	(46.0) 243.15	(53.0) 250.15	(55.0) 250.15		
75° N, 140° W	1020.5	(0) 242.15	(2.5) 248.15	(5.5) 236.15	(8.5) 213.65	(18.5) 213.65	(24.0) 208.15
		(44.0) 240.15	(52.0) 252.15	(55.0) 252.15			

The density-height profiles for the 60°N January models developed for 10°, 100°, and 140°W (Figure 13) indicate that the longitudinal variation in mean monthly densities at 40 km in winter ranges from 5 percent less than standard at 140°W to 20 percent less at 10°W. Density profiles for longitudes 10° and 140°W at 75°N (Figure 14) indicate that the longitudinal variability is slightly smaller at 75°N than at 60°N. The lowest mean monthly densities between 35 and 55 km occur at 10°W at both 60° and 75°N. This region is normally under the influence of the polar cyclone that is usually displaced toward the Eurasian continent in winter. The highest densities between 35 and 55 km occur at 140°W, reflecting the presence of the Aleutian anticyclone that normally extends well into the mesosphere in winter. At 60°N significant longitudinal variations in density are evident at altitudes (Figure 13), except at 8 km, the isopycnic level, whereas at 75°N (Figure 14) longitudinal variations only become significant above 25 km.

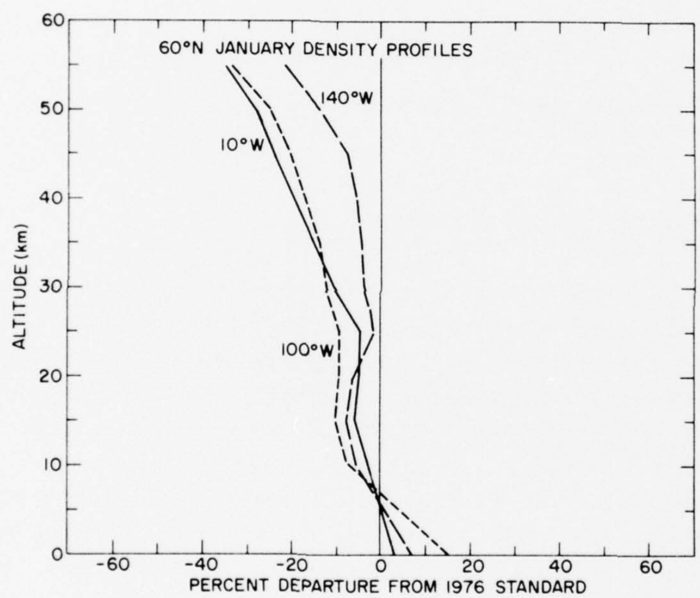

Figure 13. Density-Height Profiles for the 60°N Models at 10°, 100°, and 140°W

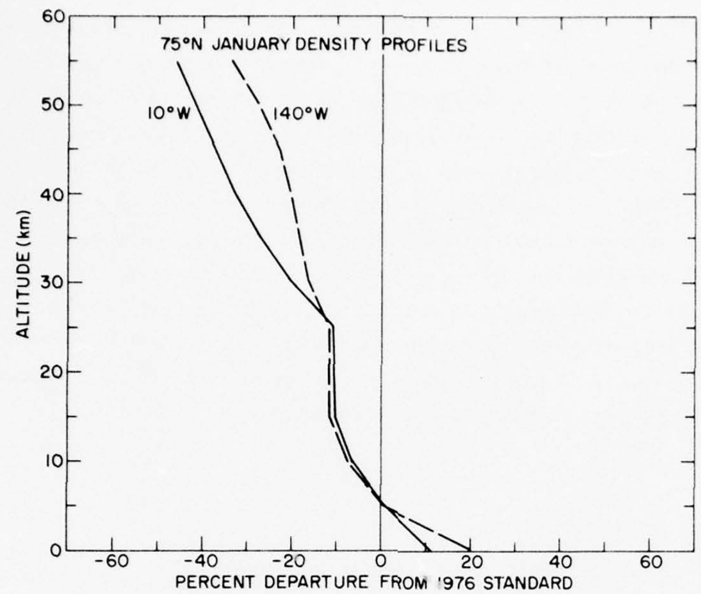

Figure 14. Density-Height Profiles for the 75°N Models at 10° and 140°W

7. ANNUAL AND SEMIANNUAL VARIATIONS

The horizontal and vertical patterns of the phases (time of maximum) and amplitude of the annual and semiannual cycles of temperature and density are important considerations in the development of internally consistent sets of monthly reference atmospheres between the Equator and the North Pole. Consequently, vertical profiles of the phases and amplitudes of the annual and semiannual oscillations of temperature and density in arctic and subarctic locations have been constructed and are shown in Figures 15 and 16. The portions of the profiles that extend from 30 to 55 km are based on MRN observations, and the portions for altitudes from 55 to 90 km are based on an analysis of experimental rocket observations. The phases and amplitudes of the annual temperature cycles (Figure 15a) are similar at Thule, Primrose Lake, Churchill, and Barrow. The outstanding feature of the profiles is the abrupt change in phase between 60 and 70 km. At altitudes below 60 km maximum temperatures occur in June or July, and at levels above 70 km maximum values occur in December and January. The observed amplitude of the annual temperature component in arctic and subarctic regions decreases from 20°K near 40 km to roughly 8°K at 65 km and then increases with altitude to about 40°K at 90 km.

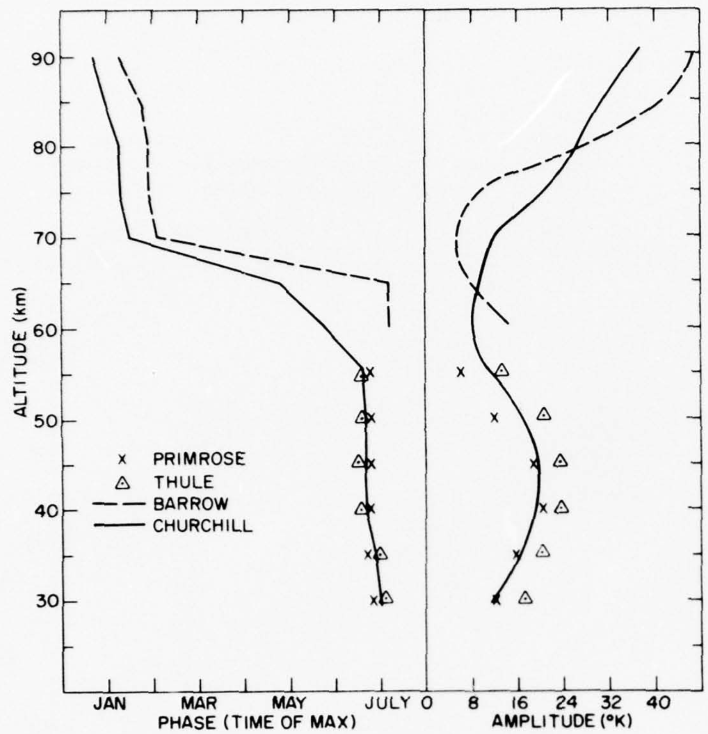

Figure 15a. Vertical Profiles of the Phases (time of maximum) and Amplitudes of the Annual Temperature Oscillations

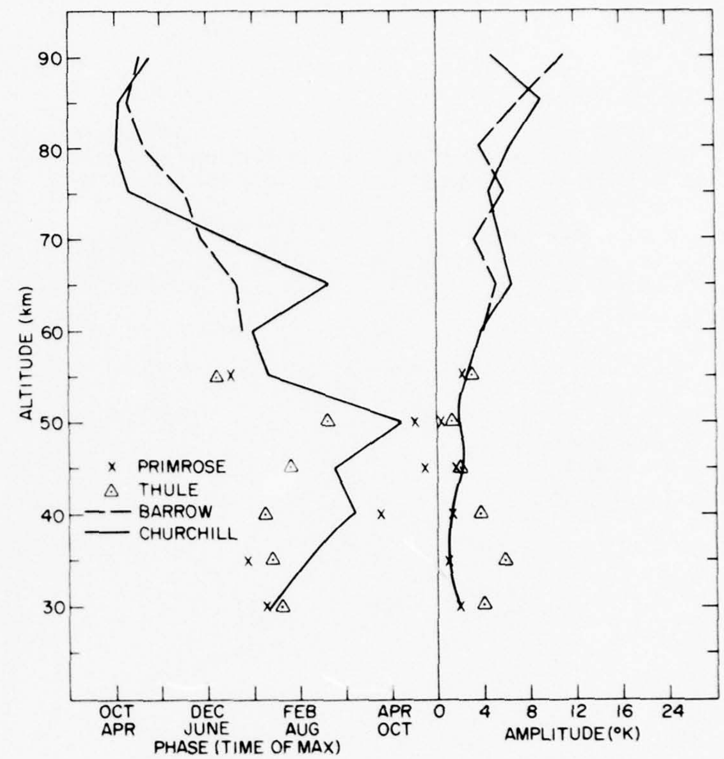

Figure 15b. Vertical Profiles of the Phases (time of maximum) and Amplitudes of the Semiannual Temperature Oscillations

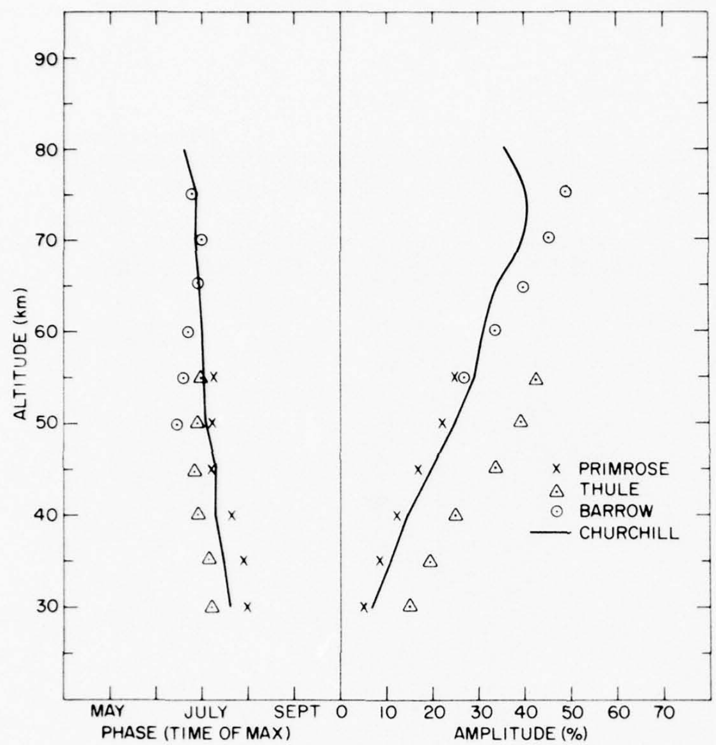

Figure 16a. Vertical Profiles of the Phases (time of maximum) and Amplitudes of the Annual Density Oscillations

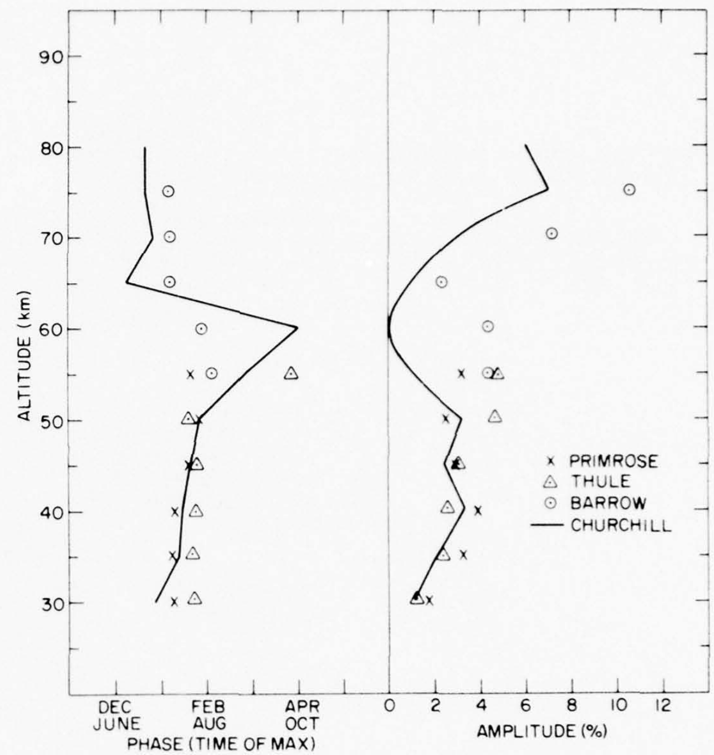

Figure 16b. Vertical Profiles of the Phases (time of maximum) and Amplitudes of the Semiannual Density Oscillations

The first maximum in the semiannual temperature cycle, Figure 15b, occurs in April at altitudes between 75 and 90 km and is propagated downward, reaching 50 km in July or August. Amplitudes are less than 4°K between 30 and 50 km and are 4 to 9°K between 50 and 90 km.

The annual density oscillations, Figure 16a, are propagated downward from the mesopause. Maximum densities occur in late June at 80 km, early July at 50 km, and mid July at 30 km. The amplitudes increase with altitude from roughly 10 percent at 30 km to 40 or 50 percent at 75 km. Variability decreases above 75 km.

The semiannual density oscillations, Figure 16b, reach maximums in mid or late January and July at altitudes between 30 and 50 km. The phases are ill-defined between 50 and 65 km where the amplitude approaches zero. Maximums occur around the first of January and July at altitudes between 65 and 80 km. Amplitudes are 1 to 2 percent at 60 km and 6 to 12 percent at 80 km.

8. DAY-TO-DAY VARIATIONS

At latitudes 60° and 75°N the observed day-to-day variations in temperature and density at altitudes up to 80 km are much larger in winter than in summer. Estimates of the median temperatures and densities and high and low values equalled or exceeded 1, 10, and 20 percent of the time in July and January are given in Tables 4 and 5 at 5-km increments of altitude. The estimates are based on data derived from an analysis of individual radiosonde and rocket observations taken in the Northern Hemisphere at locations near 60° and 75°N. Standard deviations were not used, as the temperature and density observations taken in the upper stratosphere during the winter months are not normally distributed about the monthly means.

Percentile values for Churchill were obtained graphically from plots on probability paper and are compared in Table 6 with those obtained by using mean and standard deviations for the same set of data. The 10-percent high and low values and the 1-percent high values obtained by the two methods are nearly the same in July, but are considerably different in January. Previous analyses[33] of stratospheric temperatures and densities at altitudes above 30 km have shown that the thermodynamic properties of the atmosphere tend to have a bimodal distribution during the winter months due to sudden warmings of the stratosphere. In other months the distributions appear to be nearly normal. Confidence in the estimated frequency distributions of daily values decreases rapidly with altitude above 50 km, due to the limited number of observations that are available at the higher altitudes near 60° and 75°N. Due to this lack of data, only estimated median values are given in Tables 4 and 5 for levels above 55 km at 75°N in July.

33. Cole, A.E., and Kantor, A.J. (1974) Periodic Oscillations in the Stratosphere and Mesosphere, AFCRL-TR-74-0504.

Table 4a. Median, High, and Low Percentile Temperatures for January and July at 60°N

Altitude (km)	Median (°K)	1% High (°K)	1% Low (°K)	10% High (°K)	10% Low (°K)	20% High (°K)	20% Low (°K)
JANUARY							
5	240	255	225	249	231	246	234
10	217	231	203	224	209	222	211
15	217	231	203	225	209	222	212
20	215	236	194	226	204	222	208
25	212	241	185	229	197	223	203
30	216	253	203	235	209	225	210
35	221	277	204	259	204	238	214
40	227	300	206	278	211	246	219
45	243	303	219	282	225	255	231
50	251	289	226	280	240	271	245
55	251	283	225	275	233	256	238
60	243	271	210	261	224	253	234
65	238	262	208	258	218	249	222
70	239	264	212	253	219	249	225
75	232	255	180	249	203	246	213
80	223	248	173	243	195	239	204
JULY							
5	260	271	250	266	254	264	256
10	225	238	214	233	219	231	221
15	225	235	217	231	221	229	223
20	225	233	219	230	222	229	223
25	229	236	222	233	225	232	226
30	239	245	232	243	234	241	235
35	252	258	243	256	247	253	248
40	265	272	259	269	263	268	262
45	277	287	271	283	274	280	275
50	279	290	273	286	277	284	279
55	271	278	257	275	264	273	266
60	259	273	212	265	250	263	253
65	238	259	225	253	230	248	233
70	214	239	202	226	208	222	211
75	190	202	178	196	182	194	186
80	166	180	142	176	153	174	155

Table 4b. Median, High, and Low Percentile Temperatures for January and July at 75°N

Altitude (km)	Median (°K)	1%		10%		20%	
		High (°K)	Low (°K)	High (°K)	Low (°K)	High (°K)	Low (°K)
JANUARY							
5	235	246	222	241	229	238	230
10	214	224	202	219	207	217	209
15	209	219	195	213	201	211	203
20	204	225	179	215	189	210	194
25	205	233	181	221	193	216	198
30	209	255	194	231	198	224	202
35	219	256	199	249	210	236	213
40	229	284	207	256	219	248	224
45	239	281	203	264	224	260	233
50	249	282	201	265	225	259	229
55	255	291	208	262	221	253	226
60	247	303	206	263	213	255	219
65	238	310	186	277	202	263	209
70	242	297	166	277	201	261	207
75	234	289	183	259	201	251	207
80	224	277	165	254	194	240	201
JULY							
5	254	264	244	259	248	257	250
10	229	238	219	234	223	232	225
15	230	237	225	235	228	233	229
20	230	237	227	235	228	234	229
25	230	240	226	238	227	237	229
30	243	262	233	247	235	246	240
35	256	262	238	260	246	258	250
40	268	275	252	271	260	270	262
45	281	292	268	287	275	284	278
50	284	296	270	291	279	288	280
55	281	288	254	284	270	283	275
60	268	(insufficient data above 55 km in summer)					
65	246						
70	218						
75	189						
80	161						

Table 5a. Median, High, and Low Percentile Densities for January and July at 60°N

Altitude (km)	Median (% of Std)	1%		10%		20%		U.S. Std Density (kg m^{-3})
		High	Low	High	Low	High	Low	
JANUARY								
5	+1	+6	-3	+4	-1	+2	0	7.3643-1
10	-6	+3	-15	+2	-15	-3	-10	4.1351
15	-9	-2	-15	-5	-12	-6	-11	1.9476
20	-8	-1	-15	-5	-11	-6	-10	8.8910-2
25	-7	+3	-16	-2	-12	-4	-10	4.0084
30	-10	+7	-32	+2	-18	-2	-15	1.8410
35	-12	+8	-35	+3	-27	-3	-19	8.4634-3
40	-15	+10	-36	+5	-30	-4	-20	3.9957
45	-21	+12	-39	+5	-34	-10	-24	1.9663
50	-26	+14	-43	+3	-36	-15	-29	1.0269
55	-32	+9	-48	-10	-39	-20	-35	5.6810-4
60	-36	+4	-54	-12	-40	-25	-39	3.0968
65	-36	-5	-50	-16	-46	-27	-42	1.6321
70	-37	-12	-54	-25	-49	-32	-43	8.2828-5
75	-35	-10	-53	-24	-47	-30	-42	3.9921
80	-28	-11	-53	-17	-47	-21	-40	1.8458
JULY								
5	-2	+2	-5	+1	-4	0	-3	7.3643-1
10	0	+7	-8	+4	-5	+2	-3	4.1351
15	0	+6	-7	+3	-4	+2	-2	1.9476
20	+3	+7	-2	+6	0	+5	+1	8.8910-2
25	+5	+8	+1	+7	+2	+6	+3	4.0084
30	+7	+12	-1	+9	+2	+8	+4	1.8410
35	+10	+18	0	+14	+3	+12	+7	8.4634-3
40	+15	+23	+5	+19	+10	+17	+12	3.9957
45	+20	+28	+7	+25	+13	+23	+16	1.9663
50	+25	+35	+10	+30	+16	+28	+22	1.0269
55	+27	+35	+11	+30	+16	+29	+22	5.6810-4
60	+28	+42	+11	+39	+16	+33	+22	3.0968
65	+35	+50	+11	+44	+18	+39	+28	1.6321
70	+42	+52	+12	+46	+20	+44	+30	8.2828-5
75	+44	+58	+12	+52	+20	+48	+35	3.9921
80	+40	+56	+10	+50	+18	+44	+30	1.8458

Table 5b. Median, High, and Low Percentile Densities for January and July at 75°N

Altitude (km)	Median (% of Std)	1%		10%		20%		U.S. Std Density ($kg\ m^{-3}$)
		High	Low	High	Low	High	Low	
JANUARY								
5	+2	+6	-1	+5	0	+4	+1	7.3643-1
10	-8	+2	-18	-3	-13	-5	-10	4.1351
15	-10	-1	-18	-6	-14	-8	-13	1.9476
20	-12	-1	-22	-6	-17	-8	-15	8.8910-2
25	-15	-2	-28	-8	-20	-10	-18	4.0084
30	-21	-4	-36	-9	-26	-16	-24	1.8410
35	-25	0	-43	-10	-32	-16	-30	8.4634-3
40	-29	+4	-48	-9	-38	-16	-38	3.9957
45	-33	+8	-52	-6	-45	-16	-39	1.9663
50	-38	+4	-56	-8	-48	-20	-42	1.0269
55	-44	+5	-65	-10	-56	-23	-50	5.6810-4
60	-46	0	-70	-16	-60	-32	-55	3.0968
65	-47	+1	-66	-27	-62	-35	-58	1.6321
70	-48	-1	-69	-21	-62	-35	-60	8.2828-5
75	-45	-10	-65	-25	-57	-35	-53	3.9921
80	-40	-8	-55	-24	-50	-34	-45	1.8458
JULY								
5	1	+4	-2	+3	-1	+2	0	7.3643-1
10	-4	+5	-12	+3	-10	0	-7	4.1351
15	-4	+2	-9	0	-7	-2	-6	1.9476
20	+1	+6	-4	+4	-2	+3	-1	8.8910-2
25	+1	+10	-8	+6	-3	+5	-2	4.0084
30	+7	+13	+2	+10	+5	+8	+6	1.8410
35	+12	+25	+3	+18	+8	+16	+10	8.4634-3
40	+19	+27	+6	+23	+13	+21	+16	3.9957
45	+25	+35	+10	+30	+18	+28	+21	1.9663
50	+27	+40	+10	+35	+20	+32	+24	1.0269
55	+32	+42	+10	+39	+20	+35	+25	5.6810-4
60	+37							3.0968
65	+48	(Insufficient data above 55 km in summer)						1.6321
70	+60							8.2828-5
75	+67							3.9921
80	+64							1.8458

Table 6. Churchill Density (percent departure from standard)

JANUARY										
km	Mean	σ	10% High		10% Low		1% High		1% Low	
	%	%	Est.$_\sigma$	Calc.	Est.$_\sigma$	Calc.	Est.$_\sigma$	Calc.	Est.$_\sigma$	Calc.
30	-8.9	7.5	1	1	-19	-25	9	7	-26	-32
35	-10.1	9.5	2	1	-22	-25	12	6	-32	-31
40	-10.8	10.5	3	0	-24	-21	14	5	-35	-29
45	-13.2	12.4	3	-6	-29	-25	16	2	-42	-31
50	-17.5	12.7	-1	-9	-34	-30	12	0	-47	-36
55	-23.3	13.4	-6	-14	-40	-39	8	-2	-54	-46
60	-26.1	11.6	-11	-16	-41	-39	1	0	-53	-53

JULY										
km	Mean	σ	10% High		10% Low		1% High		1% Low	
	%	%	Est.$_\sigma$	Calc.	Est.$_\sigma$	Calc.	Est.$_\sigma$	Calc.	Est.$_\sigma$	Calc.
30	7.1	1.3	9	9	5	2	10	12	4	-1
35	11.1	1.3	13	13	9	6	14	16	8	3
40	15.4	2.0	18	19	13	10	20	22	11	6
45	19.2	2.4	22	23	16	16	25	25	14	10
50	23.2	3.0	27	29	19	19	30	32	16	14
55	23.6	3.2	28	28	19	19	31	32	16	15
60	25.9	4.2	31	30	21	16	36	35	16	11

Random instrumentation errors are included in the observations that were used to determine the frequency distributions of the temperatures and densities given in Tables 4 and 5. The actual range of the day-to-day variations would be slightly smaller if the random instrumentation errors were removed. The estimated random root-mean-square (rms) instrument errors obtained from recent studies for radiosonde and meteorological rocket observations[1, 17, 34] are given below:

Sensor	Altitude (km)	Density (%)	Temperature (°K)
Radiosonde	0 to 30	<0.5	0.2
Met Rocket	30 to 50	0.5 to 1.6	0.2 to 2.0

Very little information has been published on the random observational errors associated with temperatures and densities derived from grenade, falling sphere, and pressure gauge experiments for altitudes between 50 and 80 km. Grenade and pressure gauge limitations based on theoretical studies are described in NASA reports.[18-26]

Neither extreme temperatures nor extreme densities occur simultaneously at all altitudes. Consequently, the data in Tables 4 and 5 cannot be used to represent extreme density and temperature-height profiles. The results of previous studies[35] indicate that correlation coefficients between densities at different levels decrease exponentially with altitude. The decay in correlation with altitude for levels above 8 km (the isopycnic level) is approximated reasonably well by the equation $r_h = \exp(-ah)$ where h is the layer separation in km and a equals 0.05-0.08.[35] That study also shows that densities immediately above the isopycnic level are negatively correlated with those below it. Additional research is being completed on interlevel and spatial correlations for the region between 30 and 60 km. Preliminary studies have shown a strong negative correlation between extreme winter temperatures at the stratopause and those at the mesopause.

9. DIURNAL VARIABILITY OF DENSITY

During the equinox of 19 and 20 March 1974, seven meteorological rockets (Loki Datasonde Systems) were launched within a 24-hr period at Churchill. The launchings were part of an experiment initiated by NASA[36] to examine the diurnal

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35. Cole, A.E., and Court, A. (1962) Density Distribution Interlevel Correlations and Variation with Wind, AFCRL-62-815.

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variations in the structure of the upper stratosphere and lower mesosphere. Corrections to the observed temperature data were applied following the recommendations of Krumins and Lyons.[17] Densities computed from the corrected temperature profiles for 30, 40, and 50 km were subjected to harmonic analysis, Figure 17, for diurnal and semidiurnal cycles. The combined amplitudes of the computed diurnal and semidiurnal oscillations are approximately 0.7, 1.4, and 2.4 percent of the daily mean at 30, 40, and 50 km, respectively. The harmonic analysis explains 82, 47, and 96 percent of the total variance at 30, 40, and 50 km. The observed amplitudes, however, are not much larger than the estimated rms observational errors that range from 0.4 percent at 30 km to 1.7 percent at 50 km. The amplitude of 2.4 percent at 50 km is nearly the same as the amplitude of the diurnal density oscillation observed at Wallops Island (38°N)[2] and slightly more than one half the 4-percent amplitude observed in the Tropics.[1] This is in agreement with theory that predicts larger amplitudes in the diurnal oscillations at these altitudes in the Tropics than at other latitudes.

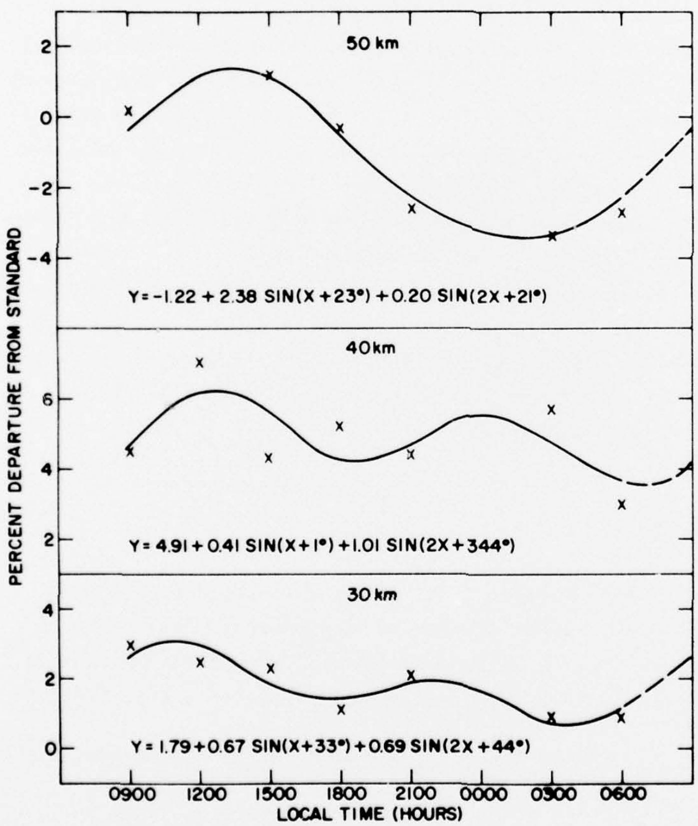

Figure 17. Sum of the Diurnal and Semidiurnal Density Oscillations Observed at Churchill on 19-20 March 1974

10. SPATIAL VARIABILITY OF DENSITY

Mean monthly latitudinal density gradients between latitudes 60° and 75°N are shown in Table 7 for altitudes between 40 and 80 km. Densities at these levels decrease toward the Pole in January and toward the Equator in July. The gradients at all levels are largest in January, with the maximum gradient occurring near 70 km. There are relatively large day-to-day variations around the mean monthly gradients at any particular level and location due to changes in synoptic conditions.

Table 7. Mean Monthly Latitudinal Density Gradients (percent change per degree of latitude in the direction of the Pole) Between 60°N and 75°N)

Altitude (km)	Jan	Apr	July	Oct
40	-1.1	-0.1	+0.2	-0.9
50	-1.1	-0.4	+0.3	-1.1
60	-1.1	-0.4	+0.4	-0.9
70	-1.2	-0.4	+0.9	-0.9
80	-1.1	-0.4	+1.1	-0.9

Estimates of the density gradients that are equalled or exceeded 5 percent of the time in January and July at altitudes between 40 and 60 km are presented in Table 8 for the region between 60° and 75°N. These estimates are based on the standard deviations of the day-to-day variations at Churchill, the mean seasonal density gradients, and the assumption that the correlation coefficient between densities at two points at the same altitude 300 miles apart is 0.96.

Table 8. Estimates of Density Gradients That are Equalled or Exceeded 5 Percent of the Time in January and July Between 60°N and 75°N. Gradient is given as percent change per 60 nautical miles when going from high to low density

Altitude (km)	Winter Gradient (%)		Summer Gradient (%)	
	East-West	North-South	East-West	North-South
40	1.2	2.1	0.2	0.4
50	1.4	2.3	0.3	0.6
60	1.3	2.2	0.5	0.8

The following relationship was used to derive the indicated extreme density gradients shown in Table 8:

$$\sigma_{xy} = \sigma \sqrt{2(1-\rho)} \tag{8}$$

where σ_{xy} is the rms difference in the density at two points 300 miles apart;

σ is the standard deviation of density, which is assumed to be constant for 300 miles; and

ρ is the correlation coefficient, which is assumed to be 0.96, at points 300 miles apart.

Zero mean seasonal gradients were assumed in calculating the east-west gradients, whereas the mean seasonal gradients in Table 7 were used in calculating the north-south extremes.

As previously mentioned, temperature and density distributions at these levels in winter tend to be bimodal rather than normal. The data in Table 6, however, indicate that standard deviations provide a conservative estimate of the 10 and 1 percent values of density at Churchill. Consequently, estimates of density gradients based on standard deviations will be on the high (or conservative) side of the actual gradient.

The decays in correlation between temperatures and between heights of pressure surfaces with increasing distance between points at the 0.4-mb (55 km) and 2-mb (43 km) surfaces were computed at 60° and 75°N. Plots for pressure heights in winter at 2 and 0.4 mb are shown in Figure 18. The data are from a 5-year sample of constant-pressure maps for 0.4- and 2-mb levels.[11-16] It was assumed that the decay in correlation between densities at two points with increasing horizontal separation would be similar to that for temperature and pressure height, since all three parameters show a similar decay in correlation with distance at radiosonde levels.[37]

37. Bertoni, E.A., and Lund, I.A. (1964) Winter Space Correlations of Pressure, Temperature, and Density to 16 km, AFCRL-64-1020.

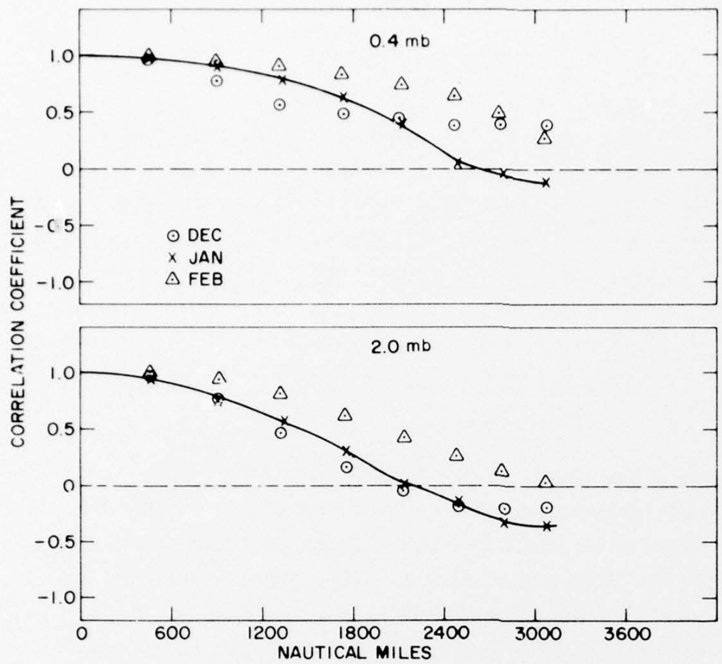

Figure 18. Horizontal Decay of Pressure-Height Correlation as a Function of Distance Between Stations at 0.4 mb and 2 mb Near 60°N

11. CONCLUSIONS

● The range of mean monthly temperatures and densities at altitudes between 10 and 90 km are given below for 60° and 75°N:

	60°N		75°N	
Altitude (km)	Mean Annual Temp (°K)	Range of Mean Monthly Temp (°K)	Mean Annual Temp (°K)	Range of Mean Monthly Temp (°K)
10	221	217 to 225	221	214 to 228
20	220	214 to 225	218	204 to 230
30	227	215 to 239	225	209 to 243
40	246	226 to 265	245	225 to 268
50	266	249 to 281	267	249 to 286
60	250	241 to 259	253	242 to 288
70	226	213 to 242	229	212 to 244
80	201	166 to 222	200	161 to 224
90	187	149 to 221	185	143 to 221

Altitude (km)	60°N Mean Annual Density (kg/m^3)	60°N Range (%) of Monthly Density	75°N Mean Annual Density (kg/m^3)	75°N Range (%) of Monthly Density
10	4.0182×10^{-1}	-3.4 to +3.5	3.8650×10^{-1}	-1.9 to + 3.3
20	8.6429×10^{-2}	-5.7 to +5.5	8.3365×10^{-2}	-5.9 to +7.5
30	1.8165×10^{-2}	-9.0 to +8.1	1.7292×10^{-2}	-15.5 to +14.4
40	3.9919×10^{-3}	-14.9 to +15.7	3.7627×10^{-3}	-24.6 to +26.5
50	1.0078×10^{-3}	-25.7 to +27.5	9.4037×10^{-4}	-32.5 to +42.6
60	2.9698×10^{-4}	-33.8 to +35.7	2.8257×10^{-4}	-40.6 to +50.0
70	8.1042×10^{-5}	-37.7 to +45.5	7.9281×10^{-5}	-45.9 to +67.4
80	1.8862×10^{-5}	-30.7 to +42.1	1.8742×10^{-5}	-41.1 to +62.8
90	3.4077×10^{-6}	-18.9 to +22.9	3.2127×10^{-6}	-23.1 to +22.3

● Longitudinal variations in the mean monthly temperature and density-height profiles for altitudes below 60 km are largest in winter in arctic and subarctic regions. The maximum longitudinal variations in the mean monthly densities, nearly 20 percent, occur at 45 km between 10° and 140°W. Longitudinal variations in the mean monthly temperatures are greatest, 14°K, near 30 km.

● Density and temperature observations in the stratosphere are not normally distributed around the monthly means during the winter months. Frequency distributions rather than standard deviations are needed to obtain accurate estimates of the probability of occurrence of extreme values at these altitudes. Estimated high and low values of densities that are equalled or exceeded 1 percent of the time at Churchill in January at 40 km are +5 and -29 percent of standard. Analogous values for 60 km are 0 and -53 percent.

● Available data indicate that the amplitudes of the diurnal variations of density at altitudes between 30 and 50 km range from 1 to 2.5 percent during the vernal equinox at 60° and 75°N. Additional observations are required before the magnitude of the diurnal oscillations of density and temperature can be more accurately determined, especially for altitudes above 50 km.

● Horizontal density gradients in the upper stratosphere are greatest in the winter in these regions. The density gradient that is equalled or exceeded 5 percent of the time in January at 50 km is estimated to be a 2.3-percent change per 60 nautical miles.

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Appendix A

Thermodynamic Properties of the Arctic and Subarctic Atmospheres

Table A1. Mean Monthly Thermodynamic Properties at 60°N

Altitude (km)	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	
						TEMPERATURE (K)								
0.000	257.15	256.65	261.65	269.15	276.65	282.65	287.15	284.15	281.15	275.15	266.15	259.15	271.40	
5.000	240.93	244.88	245.63	250.13	253.23	259.63	260.13	262.13	256.13	252.63	248.63	243.88	251.50	
10.000	217.15	218.65	219.65	222.15	223.65	224.67	225.17	224.17	221.17	220.16	218.65	217.65	221.07	
15.000	217.15	218.65	219.65	222.15	223.65	224.65	225.15	224.15	221.15	220.15	218.65	217.65	221.07	
20.000	214.66	216.16	218.65	222.15	223.65	224.65	225.15	224.15	221.15	218.67	216.66	214.17	219.99	
25.000	212.18	217.49	220.62	222.15	223.65	230.94	229.01	229.30	222.64	219.09	214.67	210.69	221.04	
30.000	216.55	221.46	222.60	227.53	234.42	238.88	239.18	236.74	230.58	223.06	218.56	215.05	227.05	
35.000	221.01	226.00	230.90	238.81	246.73	251.43	252.06	247.53	239.19	229.85	222.53	219.51	235.46	
40.000	226.43	235.99	243.63	253.07	260.59	265.29	264.93	259.90	251.07	239.75	230.33	226.85	246.49	
45.000	243.24	249.46	256.47	267.39	272.63	276.13	277.34	271.01	262.26	252.00	241.55	238.05	258.98	
50.000	250.69	255.65	265.15	274.15	279.15	280.65	279.15	275.15	267.15	260.15	255.65	249.39	266.01	
55.000	251.13	254.05	260.95	267.85	269.31	272.85	270.51	266.47	255.67	254.48	251.87	250.15	260.44	
60.000	250.11	249.10	251.09	253.10	257.51	258.10	258.71	252.70	241.90	241.20	243.02	246.63	250.26	
65.000	238.82	234.37	233.91	238.37	243.45	242.52	238.36	234.28	228.16	231.22	237.65	241.72	236.90	
70.000	238.65	232.21	228.61	228.01	223.84	218.01	214.34	213.03	215.76	226.32	236.96	241.65	226.45	
75.000	232.20	230.26	226.66	217.73	204.26	193.54	190.36	196.39	206.95	220.70	226.86	230.32	214.67	
80.000	222.43	220.93	217.13	205.17	184.71	169.11	166.42	179.93	198.15	210.93	216.65	218.59	200.85	
85.000	214.65	211.17	204.93	192.48	167.96	154.66	154.16	170.17	189.37	204.15	216.65	214.43	191.23	
90.000	214.65	205.15	193.65	179.81	163.15	150.15	149.29	160.43	182.15	204.15	216.65	221.25	186.71	
						PRESSURE (mb)								
0.000	1.0144	1.0146	1.0143	1.0134	1.0133	1.0110	1.0099	1.0107	1.0113	1.0106	1.0125	1.0126	1.0124	+3*
5.000	5.1610	5.1929	5.2145	5.2671	5.3318	5.3961	5.4053	5.4044	5.3634	5.2995	5.2381	5.1853	5.2883	+2
10.000	2.4192	2.4529	2.4811	2.5323	2.5802	2.6639	2.6724	2.6752	2.6204	2.5720	2.4964	2.4412	2.5505	
15.000	1.1039	1.1253	1.1423	1.1761	1.2046	1.2478	1.2539	1.2510	1.2128	1.1863	1.1453	1.1160	1.1804	
20.000	5.0213	5.1466	5.2569	5.4693	5.6304	5.8525	5.8909	5.8575	5.6205	5.4712	5.2425	5.0762	5.4613	+1
25.000	2.2658	2.3449	2.4260	2.5463	2.6348	2.7707	2.7776	2.7620	2.6090	2.5105	2.3853	2.2821	2.5263	
30.000	1.0271	1.0829	1.1287	1.1976	1.2562	1.3461	1.3455	1.3340	1.2344	1.1659	1.0902	1.0287	1.1864	
35.000	4.7374	5.0790	5.3484	5.7924	6.2074	6.7372	6.7531	6.6190	5.9986	5.5068	5.0599	4.7196	5.7132	+0
40.000	2.2252	2.4345	2.6221	2.9122	3.1874	3.5016	3.5111	3.3993	3.0096	2.6804	2.3978	2.2125	2.8411	
45.000	1.0834	1.2149	1.3349	1.5223	1.6942	1.8786	1.8848	1.8018	1.5603	1.3489	1.1722	1.0700	1.4639	
50.000	0.5479	0.6236	0.7007	0.8181	0.9220	1.0282	1.0297	0.9741	0.8271	0.7009	0.5953	0.5359	0.7753	
55.000	2.8042	3.2270	3.7071	4.4154	5.0011	5.6210	5.5969	5.2524	4.3556	3.6602	3.0762	2.7349	4.1210	-1
60.000	1.4346	1.6551	1.9233	2.3164	2.6428	2.9849	2.9661	2.7495	2.2168	1.8581	1.5601	1.3926	2.1417	
65.000	0.7223	0.8268	0.9628	1.1703	1.3555	1.5286	1.5151	1.3839	1.0857	0.9106	0.7739	0.7006	1.0781	
70.000	3.5808	4.0321	4.6483	5.7060	6.6171	7.3818	7.2253	6.5383	5.0963	4.3796	3.8253	3.5038	5.2112	-2
75.000	1.7658	1.9566	2.2299	2.6944	3.0282	3.2724	3.1593	2.8877	2.3101	2.0748	1.8594	1.7259	2.4137	
80.000	0.8471	0.9340	1.0542	1.2234	1.2826	1.3014	1.2375	1.1880	1.0130	0.9571	0.8751	0.8202	1.0612	
85.000	3.9398	4.3178	4.7843	5.2890	4.9503	4.5717	4.3079	4.5836	4.2852	4.2698	4.0545	3.7676	4.4267	-3
90.000	1.8144	1.9323	2.0714	2.1624	1.8067	1.5320	1.4383	1.6743	1.7437	1.8895	1.8807	1.7548	1.8084	
						DENSITY (kg m^{-3})								
0.000	1.3742	1.3771	1.3504	1.3116	1.2759	1.2460	1.2252	1.2391	1.2530	1.2795	1.3252	1.3612	1.3015	+0*
5.000	7.4623	7.3874	7.3954	7.3356	7.3348	7.2403	7.2388	7.1823	7.2948	7.3077	7.3394	7.4069	7.3271	-1
10.000	3.8811	3.9081	3.9351	3.9711	4.0191	4.1306	4.1345	4.1573	4.1275	4.0696	3.9774	3.9074	4.0182	
15.000	1.7710	1.7930	1.8118	1.8444	1.8763	1.9351	1.9402	1.9443	1.9105	1.8772	1.8248	1.7863	1.8596	
20.000	8.1486	8.2940	8.3754	8.5768	8.7702	9.0756	9.1149	9.1036	8.8538	8.7162	8.4292	8.2566	8.6429	-2
25.000	3.7201	3.7559	3.8308	3.9931	4.1041	4.1795	4.2252	4.1963	4.0823	3.9918	3.8708	3.7732	3.9769	
30.000	1.6522	1.7034	1.7664	1.8336	1.8668	1.9630	1.9598	1.9631	1.8650	1.8208	1.7377	1.6664	1.8165	
35.000	7.4672	7.8290	8.0694	8.4497	8.7642	9.3344	9.3330	9.3154	8.7364	8.3461	7.9211	7.4900	8.4213	-3
40.000	3.4235	3.5938	3.7494	4.0089	4.2610	4.5981	4.6169	4.5564	4.1759	3.8948	3.6266	3.3977	3.9919	
45.000	1.5517	1.6967	1.8132	1.9832	2.1648	2.3701	2.3675	2.3161	2.0726	1.8647	1.6905	1.5659	1.9548	
50.000	0.7615	0.8497	0.9206	1.0396	1.1506	1.2763	1.2850	1.2333	1.0786	0.9386	0.8112	0.7485	1.0078	
55.000	3.8901	4.4251	4.9489	5.7426	6.4692	7.1766	7.2077	6.8666	5.9347	5.0105	4.2548	3.8088	5.4780	-4
60.000	1.9982	2.3146	2.6684	3.1882	3.5752	4.0288	3.9941	3.7903	3.1924	2.6836	2.2364	1.9670	2.9698	
65.000	1.0536	1.2289	1.4339	1.7103	1.9397	2.1957	2.2143	2.0578	1.6577	1.3720	1.1345	1.0097	1.5840	
70.000	0.5227	0.6048	0.7083	0.8717	1.0298	1.1795	1.1742	1.0691	0.8228	0.6741	0.5623	0.5051	0.8104	
75.000	2.6492	2.9602	3.4273	4.3109	5.1645	5.8901	5.7814	5.1222	3.8887	3.2750	2.8575	2.6105	3.9948	-5
80.000	1.3267	1.4728	1.6914	2.0773	2.4189	2.6809	2.5905	2.3002	1.7810	1.5808	1.4072	1.3072	1.8862	
85.000	0.6394	0.7122	0.8132	0.9572	1.0267	1.0297	0.9734	0.9383	0.7883	0.7286	0.6519	0.6120	0.8226	
90.000	2.9448	3.2813	3.7264	4.1894	3.8579	3.5545	3.3563	3.6356	3.3349	3.2244	3.0241	2.7631	3.4077	-6

*Power of 10 by which preceding numbers should be multiplied.

Table A2. Mean Monthly Thermodynamic Properties at 75°N

Altitude (km)	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	
							TEMPERATURE (K)							
0.000	248.15	247.65	248.65	255.15	264.15	272.65	275.65	274.65	270.15	262.65	253.15	251.15	260.32	
5.000	234.86	235.00	236.36	239.36	245.10	250.59	254.10	253.09	246.10	242.35	236.86	236.10	242.49	
10.000	214.14	214.94	217.90	222.56	225.65	227.65	228.55	225.65	223.15	219.65	217.65	214.24	220.98	
15.000	209.15	211.95	219.65	224.15	228.15	229.65	230.15	228.14	224.65	219.65	216.15	211.25	221.06	
20.000	204.16	204.92	214.66	224.15	228.15	229.65	230.15	228.15	222.90	215.66	211.16	208.26	218.50	
25.000	204.72	209.94	217.62	224.15	228.15	231.62	230.15	228.15	222.65	210.69	208.37	205.27	218.46	
30.000	209.00	216.40	222.78	227.61	233.46	243.47	242.95	236.71	226.50	216.56	210.86	210.53	224.74	
35.000	218.92	222.85	230.23	236.54	246.43	255.37	255.85	249.11	236.42	222.51	219.92	217.98	234.34	
40.000	228.82	229.29	237.99	248.03	260.30	267.26	268.24	261.49	246.32	235.71	229.82	225.40	244.89	
45.000	238.71	240.86	250.36	263.86	274.14	279.13	280.61	273.86	261.96	249.06	239.71	236.44	257.39	
50.000	248.59	253.20	262.70	274.15	283.15	285.65	283.65	278.15	270.65	262.39	254.06	250.27	267.22	
55.000	255.15	260.15	266.61	268.86	277.53	280.69	280.77	274.84	270.65	262.60	257.66	256.31	267.65	
60.000	247.37	246.42	249.39	253.11	260.80	285.92	268.46	263.45	252.35	244.88	241.91	245.48	253.30	
65.000	239.02	233.34	232.19	237.38	244.09	251.18	246.32	240.35	232.69	227.19	235.39	241.39	238.38	
70.000	241.66	235.30	230.19	226.75	225.45	221.78	217.86	217.29	217.86	227.15	237.84	243.84	228.61	
75.000	233.56	231.68	228.23	217.44	201.94	192.38	189.44	194.26	208.06	223.56	229.56	234.70	215.40	
80.000	223.77	223.85	216.43	204.09	178.46	163.03	161.07	171.85	198.27	213.77	221.15	223.94	199.97	
85.000	214.15	216.03	204.22	189.44	165.01	145.11	146.62	164.03	188.51	205.15	221.15	219.00	189.87	
90.000	214.15	208.23	193.15	176.15	155.25	142.67	144.67	156.23	180.65	205.15	221.15	226.31	185.31	
							PRESSURE (mb)							
0.000	1.0147	1.0159	1.0175	1.0169	1.0170	1.0131	1.0111	1.0115	1.0116	1.0092	1.0134	1.0128	1.0137	+3*
5.000	5.0673	5.0795	5.0921	5.1404	5.2374	5.3088	5.3405	5.3310	5.2393	5.1655	5.0953	5.0812	5.1815	+2
10.000	2.3472	2.3482	2.3739	2.4228	2.5044	2.5638	2.6077	2.5854	2.5058	2.4368	2.3784	2.3550	2.4525	
15.000	1.0486	1.0562	1.0900	1.1315	1.1836	1.2185	1.2404	1.2193	1.1720	1.1211	1.0856	1.0565	1.1353	
20.000	4.6004	4.6701	4.9767	5.2942	5.6118	5.8056	5.9195	5.7813	5.4816	5.1350	4.8930	4.6920	5.2384	+1
25.000	1.9961	2.0524	2.2664	2.4798	2.6638	2.7763	2.8281	2.7443	2.5547	2.3131	2.1693	2.0620	2.4089	
30.000	0.8768	0.9256	1.0465	1.1656	1.2756	1.3584	1.3795	1.3165	1.1949	1.0448	0.9653	0.9083	1.1215	
35.000	3.9709	4.2789	4.9520	5.6155	6.2862	6.8852	6.9917	6.5520	5.7457	4.8282	4.3885	4.1181	5.3844	+0
40.000	1.8647	2.0242	2.4025	2.7863	3.2232	3.6030	3.6654	3.3767	2.8501	2.3059	2.0677	1.9196	2.6741	
45.000	0.9051	0.9854	1.2026	1.4397	1.7126	1.9412	1.9802	1.7962	1.4654	1.1484	1.0067	0.9211	1.3754	
50.000	4.5292	4.9777	6.2305	7.7220	9.3803	1.0714	1.0917	9.7787	7.8140	5.9371	5.0754	4.6051	7.3069	-1
55.000	2.3274	2.5925	3.3105	4.1693	5.1646	5.9318	6.0250	5.3309	4.1940	3.1304	2.6396	2.3800	3.9330	
60.000	1.1926	1.3362	1.7248	2.1886	2.7646	3.2057	3.2658	2.8584	2.2076	1.6132	1.3461	1.2175	2.0768	
65.000	0.5979	0.6620	0.8586	1.1034	1.4213	1.6743	1.7085	1.4671	1.1044	0.7918	0.6616	0.6080	1.0550	
70.000	2.9720	3.2375	4.1581	5.3494	6.9724	8.2343	8.2902	7.0478	5.2249	3.7856	3.2579	3.0468	5.1314	-2
75.000	1.4725	1.5866	2.0034	2.5175	3.1834	3.6646	3.6397	3.1222	2.3807	1.8080	1.5949	1.5167	2.3742	
80.000	0.7089	0.7617	0.9453	1.1411	1.3208	1.4279	1.3997	1.2499	1.0457	0.8419	0.7582	0.7317	1.0278	
85.000	3.3078	3.5672	4.2752	4.8854	4.9588	4.7151	4.6169	4.6274	4.4122	3.7881	3.5657	3.4216	4.1785	-3
90.000	1.5194	1.6264	1.8440	1.9569	1.7515	1.4814	1.4709	1.6347	1.7822	1.6817	1.6787	1.6190	1.6706	
							DENSITY (kg m^{-3})							
0.000	1.4244	1.4290	1.4255	1.3884	1.3412	1.2944	1.2778	1.2829	1.3044	1.3385	1.3945	1.4048	1.3588	+0*
5.000	7.5164	7.5298	7.5053	7.4814	7.4439	7.3799	7.3217	7.3377	7.4164	7.4251	7.4941	7.4972	7.4457	-1
10.000	3.8185	3.8058	3.7952	3.7924	3.8663	3.9232	3.9747	3.9914	3.9118	3.8648	3.8069	3.8294	3.8650	
15.000	1.7466	1.7360	1.7288	1.7586	1.8072	1.8484	1.8775	1.8618	1.8175	1.7781	1.7496	1.7423	1.7877	
20.000	7.8497	7.9389	8.0763	8.2881	8.5689	8.8069	8.9601	8.8276	8.5668	8.2945	8.0721	7.8486	8.3365	-2
25.000	3.3967	3.4056	3.6281	3.8541	4.0675	4.1755	4.2808	4.1903	3.9972	3.8246	3.6266	3.4994	3.8289	
30.000	1.4615	1.4901	1.6363	1.7839	1.9034	1.9437	1.9781	1.9374	1.8379	1.6807	1.5948	1.5029	1.7292	
35.000	6.3188	6.6888	7.4931	8.2701	8.8865	9.3923	9.5197	9.1625	8.4663	7.5591	6.9515	6.5815	7.9409	-3
40.000	2.8388	3.0755	3.5166	3.9134	4.3137	4.6964	4.7601	4.4985	4.0308	3.4080	3.1341	2.9667	3.7627	
45.000	1.3208	1.4252	1.6734	1.9008	2.1763	2.4227	2.4584	2.2848	1.9488	1.6062	1.4630	1.3572	1.8365	
50.000	0.6347	0.6848	0.8262	0.9812	1.1540	1.3067	1.3408	1.2247	1.0057	0.7882	0.6959	0.6410	0.9403	
55.000	3.1777	3.4717	4.3256	5.4022	6.4827	7.3619	7.4756	6.7569	5.3984	4.1528	3.5688	3.2348	5.0674	-4
60.000	1.6796	1.8890	2.4093	3.0122	3.6929	4.1995	4.2378	3.7797	3.0476	2.2949	1.9385	1.7278	2.8257	
65.000	0.8715	0.9884	1.2882	1.6193	2.0285	2.3221	2.4164	2.1264	1.6533	1.2141	0.9791	0.8774	1.5321	
70.000	0.4284	0.4793	0.6292	0.8218	1.0773	1.2934	1.3256	1.1299	0.8354	0.5805	0.4771	0.4352	0.7928	
75.000	2.1963	2.3858	3.0579	4.0334	5.4918	6.6358	6.6930	5.5988	3.9861	2.8174	2.4204	2.2513	3.9640	-5
80.000	1.1037	1.1854	1.5215	1.9477	2.5783	3.0511	3.0274	2.5337	1.8373	1.3719	1.1944	1.1383	1.8742	
85.000	0.5380	0.5752	0.7292	0.8983	1.0468	1.1319	1.0969	0.9827	0.8153	0.6432	0.5617	0.5442	0.7970	
90.000	2.4717	2.7209	3.3259	3.8701	3.9301	3.6171	3.5420	3.6450	3.4370	2.8557	2.6445	2.4922	3.2127	-6

*Power of 10 by which preceding numbers should be multiplied.

Table A3. Mean Monthly Thermodynamic Properties for January at Specified Longitudes

Altitude (km)	60°N			75°N		
	10°W	100°W	140°W	10°W	140°W	
	TEMPERATURE (K)					
0.000	278.15	246.15	269.15	257.65	242.15	
5.000	247.13	237.13	244.93	238.10	238.12	
10.000	216.16	217.15	221.15	213.64	213.65	
15.000	216.15	216.56	221.15	211.15	213.65	
20.000	212.18	213.57	221.15	206.40	212.16	
25.000	203.45	212.08	216.27	195.15	209.68	
30.000	210.40	217.04	222.22	203.39	217.63	
35.000	218.11	223.42	228.17	213.81	225.56	
40.000	229.49	232.65	234.03	226.51	233.49	
45.000	240.85	245.00	239.46	239.86	241.32	
50.000	252.19	251.82	245.83	246.87	248.73	
55.000	257.55	252.15	254.15	250.15	252.15	
	PRESSURE (mb)					
0.000	1.0025	1.0175	1.0102	1.0065	1.0205	+3*
5.000	5.2259	5.0779	5.2135	5.0754	5.0638	+2
10.000	2.4991	2.3783	2.4764	2.3628	2.3493	
15.000	1.1363	1.0850	1.1462	1.0586	1.0575	
20.000	5.1428	4.9201	5.3116	4.6998	4.7625	+1
25.000	2.2580	2.2101	2.4346	2.0056	2.1190	
30.000	0.9949	1.0027	1.1233	0.8524	0.9573	
35.000	4.5093	4.6437	5.2968	3.7824	4.4558	+0
40.000	2.1184	2.2084	2.5490	1.7519	2.1318	
45.000	1.0334	1.0892	1.2496	0.8487	1.0464	
50.000	5.2165	5.5378	6.2323	4.2534	5.2570	-1
55.000	2.7055	2.8414	3.1908	2.1630	2.6900	
	DENSITY (kg m^{-3})					
0.000	1.2555	1.4400	1.3075	1.3608	1.4681	+0*
5.000	7.3666	7.4598	7.4151	7.4258	7.4083	-1
10.000	4.0275	3.8155	3.9010	3.8527	3.8306	
15.000	1.8313	1.7455	1.8055	1.7465	1.7243	
20.000	8.4435	8.0254	8.3672	7.9325	7.8198	-2
25.000	3.8662	3.6304	3.9216	3.5802	3.5205	
30.000	1.6474	1.6094	1.7610	1.4600	1.5325	
35.000	7.2023	7.2404	8.0870	6.1627	6.8815	-3
40.000	3.2158	3.3069	3.7944	2.6943	3.1806	
45.000	1.4947	1.5487	1.8179	1.2327	1.5106	
50.000	7.2057	7.6608	8.8318	6.0021	7.3628	-4
55.000	3.6596	3.9257	4.3737	3.0123	3.7165	

*Power of 10 by which preceding numbers should be multiplied.